ASSESS FIELD TECHNIQUES USED TO DETERMINE IN SITU BULK DENSITY OF COAL AND PLAN AN APPROPRIATE PROGRAM OF FIELD WORK IN WESTERN CANADA

FINAL REPORT

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EXECUTIVE SUMMARY

The determination of in-place coal reserves requires knowledge of the volume of coal and the in-situ bulk density applicable to that volume. Assessing the volume is a well understood task, and a reliability factor can be assigned to the results of that assessment. However, to determine the in-situ tonnage, that volume must be multiplied by the in-situ bulk density, a factor that can be difficult to determine with certainty.

Natural coal may be considered to consist of three fractions:

- pure coal;
- mineral matter; and
- porosity containing water and/or gasses.

Generally the first two fractions receive a great deal of attention from coal mine operators, explorationists, and researchers, while the third is sometimes neglected. In some cases laboratory determined specific gravity has been considered to be equivalent to in situ density. Because the procedure of determining specific gravity in a laboratory involves crushing the coal samples there is an inevitable loss of porosity and pore fluids, and specific gravity will not be representative of in situ bulk density. The magnitude of any errors introduced by the use of specific gravity will be a function of the inherent porosity of the coal, the size distribution of the pores and the amount of fracture porosity in situ.

There are two general types of porosity in coal. Inherent porosity exists within and between the coal macerals and ash

minerals. Fracture porosity is superimposed on the coal as cleats and fractured or sheared zones.

The inherent pores in coal are usually classified by size:

- macropores (diameter greater than 200 nm);
- transitional pores (1.6 to 200 nm); and
- micropores (diameter less than 1.6 nm).

The percentage of inherent porosity and the size distribution of pores changes with coal rank, but the relationship between rank, porosity and pore size is not clear cut. Low rank coals are known to have an open structure with an extended system of coarse pores. Investigations by lignite and sub-bituminous coal mine operators have demonstrated that the use of laboratory determined specific gravity values for reserve estimation can have a significant inflationary effect on reserves (in lignite it is not uncommon for specific gravity to be 20%, or more, greater than bulk density). The data base is not available to make conclusions about the impact of using specific gravity for reserve estimations for western Canadian bituminous coals and anthracite.

Fracture porosity will have a minor and local effect on in situ bulk density of plains coals and lignites. However, in some places in foothills and mountain coal deposits shearing can substantially increase the in situ porosity of coal seams. Extreme examples can be seen in tectonically thickened deposits (Coal Valley, Coal Mountain, Tent Mountain, etc.). Unfortunately it is practically impossible to obtain an undisturbed sample of fracture porosity, and it must be studied in-situ. Although there are a few studies of coal seam aquifers which deal with flow parameters, no data have been found regarding the fracture porosity of coal.

Downhole geophysics offers possibilities for the measurement of bulk density in situ. Geophysical techniques avoid the problems associated with sample preparation and fracture porosity because the data produced are, in theory at least, representative of the material in situ. There are, however, other problems with borehole effects, calibration and interpretation. Highly sophisticated techniques have been developed which minimize the impact of these problems, and operators may find that under some circumstances (including the absence of serious borehole effects) geophysical data from a well calibrated, high resolution sidewall density sonde can be more meaningful than laboratory data.

Western Canadian mine operators are aware that porosity, both inherent and resulting from fractures, can have an impact on in situ bulk density. A wide variety of techniques to determine density are used by the operators, including bulk sampling, borehole geophysics, laboratory determined specific gravity data (and derived equations), core and lump coal bulk density data, and historical tonnage values.

The most practical information on coal density determination has come from the coal mine operators themselves. Sophisticated research studies designed to measure total porosity, including transitional and microporosity are inappropriate as it is difficult to isolate the effect of the coarser macroporosity that is significant to reserve calculation. A field testing program designed to evaluate the problem from the mine operators' point of view, for a variety of coal ranks, would help to resolve the practical questions about density determination. A number of coal mine operators and explorationists have expressed interest in such

a program, and would be willing to participate if they are conducting drilling programs at the time of the study.

The field and laboratory program would obtain the data necessary to define the magnitude of the difference between in situ bulk density and specific gravity and it would provide information necessary to further evaluate the impact of fracture porosity on in situ bulk density.

Conclusions reached during this review and assessment are:

1. There can be very significant differences between true (specific gravity) and apparent (bulk) densities in some coals.

2. Western Canadian coal mine operators recognize that a problem may exist, in some cases, in the determination of in situ bulk density, but for most deposits the magnitude of the problem is not known, nor is the data base available for a proper assessment.

3. Those operators who are planning new mine developments expressed the most interest in the problem and were most aware of the implications.

4. Most operators with a sufficiently long production history use techniques for reserve estimation that have evolved during the course of mining operations.

5. From a technical perspective, it is difficult to estimate the effect of porosity on specific gravity and density because there is so little data available on pore size distribution.

6. With one exception, all the published and unpublished data on porosity (or specific gravity and bulk density) showed the same result regardless of analytical techniques: There are no significant trends between porosity and rank (fixed carbon) or porosity and ash.

7. The evaluation of fracture porosity is an extremely difficult problem which has been the subject of decades of research in the oil industry. In situ geophysical techniques are the most practical approach, because it is not possible to obtain undisturbed core samples, but there is no universally effective method available at present.

Recommendations include:

1. Because many mine operators are now beginning to conduct geophysical logging programs with their own equipment the need for a common standard calibration facility is becoming more important. Work on the facility at the Institute of Sedimentary and Petroleum Geology should continue.

2. A field and laboratory testing programs should be undertaken to obtain the data necessary to adequately assess the implications of sampling and laboratory techniques on density factors to be used for reserve estimation, and to better assess the effects of fracturing and shearing on in situ bulk density of coal.

SOMMAIRE

Afin de déterminer les réserves de charbon in situ, il est nécessaire de connaître le volume du charbon ainsi que la densité apparente in situ applicable à ce volume. L'évaluation du volume est une tâche bien comprise et les résultats de cette évaluation sont fiables. Cependant, afin de déterminer le tonnage in situ, ce volume doit être multiplié par la densité apparente in situ, un élément qui peut être difficile à évaluer avec certitude.

Le charbon nature comprend trois parties:

- le charbon pur
- les matières minérales
- la porosité contenant de l'eau et/ou des gaz.

Généralement, les exploitants et les gens qui travaillent dans la recherche et l'exploration accordent beaucoup d'attention aux deux premières parties alors que la troisième est quelquefois négligée. En certains cas, la gravité poids spécifique déterminée en laboratoire a été considérée comme étant l'équivalent de la densité apparente in situ. Comme la méthode utilisée pour déterminer la gravité spécifique en laboratoire nécessite l'écrasement des échantillons de charbon, il se produit une perte inévitable de porosité et de fluides de pores, ce qui donne une gravité poids spécifique ne représentant pas la densité apparente in situ. L'importance des écarts résultant de l'emploi de la gravité poids spécifique dépendra de la porosité inhérente au charbon, de la distribution des pores (selon leur grandeur) et de la quantité de porosité de fracture in situ.

Deux types généraux de porosité existent dans le charbon. Une porosité inhérente existe à l'intérieur et entre les matières macérales et les minéraux des cendres tandis qu'une porosité de fracture est superposée sous forme de peignes et de zones fracturées ou cisaillées.

Les pores inhérents au charbon sont généralement classifiés selon leur grandeur:

- les macropores (ayant un diamètre de plus de 200 nm)
- les pores intermédiaires (1.6 à 200 nm) et
- les micropores (ayant un diamètre de moins de 1.6 nm).

Le pourcentage de la porosité inhérente et de la distribution des pores d'après leur grandeur varie selon la catégorie du charbon mais la relation entre la catégorie, la porosité et la grandeur des pores n'est pas évidente. Les charbons de catégorie inférieure sont reconnus comme ayant un vaste système de pores grossières. Des recherches faites par les exploitants de mine de charbon "lignitic and subbituminous" ont démontré que l'emploi des valeurs de la gravité spécifique déterminées en laboratoire et utilisées pour l'évaluation des réserves peuvent indiquer une augmentation excessive des réserves (en ce qui concerne la lignite, il arrive assez souvent que la gravité spécifique soit de plus de 20% plus grande que la densité apparente). Il n'y a pas de base de données disponible qui aiderait à tirer des conclusions sur l'effet de l'emploi de la gravité spécifique sur les évaluations des réserves des houilles grasses et de l'anthracite de l'Ouest canadien.

La porosité de fracture aura un effet local et mineur sur la densité apparente in situ des charbons "lignitic" des prairies. Cependant, en certains cas, dans les dépôts de charbon des Rocheuses et des Contreforts, l'écrasement peut accroître substantiellement la porosité in situ des couches de charbon. Des exemples exceptionnels se rencontrent dans les dépôts épaissis de manière tectonique (Coal Valley, Coal Mountain, Tent Mountain,etc.). Malheureusement, il est pratiquement impossible d'obtenir un échantillon non modifié d'une porosité de fracture. Ce type de porosité doit donc être étudié sur place. Bien qu'il existe quelques études sur des couches aquifères de charbon se rapportant aux paramètres de débit, il est impossible de trouver des données sur la porosité de fracture du charbon.

La densité apparente in situ pourrait être mesurée par des trous de sondage géophysiques. Les techniques géophysiques permettent d'éviter les problèmes associés à la préparation d'échantillon et à la porosité de fracture parce que les données obtenues représentent, en théorie du moins, le charbon in situ. Cependant, d'autres problèmes se trouvent associés aux effets des trous de sondage, au calibrage et à l'interprétation. Il existe des techniques très sophistiquées qui réduisent les répercussions de ces problèmes et les exploitants peuvent s'attendre à ce que, sous certaines conditions, (y compris l'absence d'effets graves des trous de sondage) les données géophysiques d'un sondage à haute résolution, prélevé latéralement et bien équilibré, soient plus utiles que les données en laboratoire.

Les exploitants de l'Ouest canadien savent que la porosité inhérente et la porosité de fracture influencent la densité apparente. Ils utilisent plusieurs techniques pour déterminer

cette densité y compris l'échantillonnage en masse, des trous de forage géophysiques, les données (et leurs équations dérivées) de la gravité poids spécifique déterminées en laboratoire, les données de densité apparente provenant des carottes de sondage et de morceaux de charbon ainsi que les facteurs de tonnage déjà acquis.

L'information la plus pratique pour déterminer la densité du charbon provient des exploitants eux-mêmes. Des études sophistiquées visant à mesurer la porosité totale, y compris les pores intermédiaires et les micropores, sont inappropriées parce qu'il est très difficile d'isoler l'effet des macropores, ce qui est un facteur important pour l'évaluation des réserves. Un programme de sondage sur terrain visant à évaluer le problème selon le point de vue des exploitants et portant sur une variété de classes de charbon aiderait à résoudre les questions d'ordre pratique concernant la détermination de la densité. Un certain nombre de gens impliqués dans l'exploration et l'exploitation du charbon ont exprimé leur intérêt dans un tel programme et y participeraient volontiers s'ils étaient en train d'effectuer des forages au moment où cette étude aurait lieu.

Cette étude sur terrain et en laboratoire fournirait les données nécessaires à évaluer l'importance de la différence qu'il existe entre la densité apparente in situ et la gravité spécifique et elle donnerait aussi l'information nécessaire pour déterminer les répercussions de la porosité de fracture sur la densité apparente in situ.

Le présent rapport permet de tirer les conclusions suivantes:

1. Pour certains charbons, il peut y avoir une différence importante entre la densité réelle (gravité poids spécifique) et la densité apparente.

2. Les exploitants de charbon de l'Ouest canadien reconnaissent qu'en certains cas un problème peut exister dans la détermination de la densité apparente in situ et que, pour la plupart des dépôts, l'importance du problème ainsi que les données de base sont inconnus.

3. Les exploitants qui projettent de nouveaux développements miniers sont ceux qui sont le plus intéressés à ce problème et à ses implications.

4. Pour l'évaluation des réserves, la plupart des exploitants dont les exploitations existent depuis un certain temps emploient des techniques qui ont été développées au cours de l'exploitation de la mine.

5. D'un point de vue technique, il est difficile d'estimer l'effet de la porosité sur la gravité spécifique et sur la densité parce qu'il y a tellement peu de données disponibles sur la distribution des pores selon leur grandeur.

6. A une exception près, toutes les données publiées et non publiées sur la porosité (ou la gravité spécifique et la densité apparente) démontrent les mêmes résultats quelque soit les techniques d'analyse utilisées: il n'y a pas de tendances significatives entre la porosité et la classe (matière carbonée solide obtenue après combustion, autre que les cendres) ou la porosité et les cendres.

7. L'évaluation de la porosité de fracture est un problème extrèmement difficile. L'industrie pétrolière a fait des recherches en ce domaine depuis plusieurs décades. L'emploi de techniques géophysiques in situ semble être la façon la plus pratique d'aborder le problème parce qu'il est autrement impossible d'obtenir des échantillons non modifiés. Cependant, il n'existe pas de méthodes effectives universellement reconnues actuellement.

Les recommendations de ce rapport comprennent:

1. Comme plusieurs exploitants commencent à faire des programmes de sondage géophysique avec leur propre équipement, le besoin de disposer d'une installation de calibrage uniformisée se fait de plus en plus sentir. C'est pourquoi l'établissement d'une telle installation à l'Institut de géologie sédimentaire et pétrolière devrait continuer.

2. Des programmes de sondage sur terrain et en laboratoire devraient être entrepris afin d'obtenir les données nécessaires à l'évaluation adéquate des implications que les techniques d'échantillonnage et de laboratoire ont sur les valeurs de densité employées dans l'évaluation des réserves. Ces programmes serviraient aussi à mieux évaluer les effets que les fractures et l'écrasement ont sur la densité apparente in situ du charbon.

SECTION 1

INTRODUCTION

This report has been prepared under DSS Contract No. 23440-6-9057/01-SQ, and concerns current practices in the determination of in-situ coal density in Western Canada, particularly at operating mines. It describes the potential problems (Section 2), the theoretical background (Sections 3 to 5) and current practices (Section 6), and it sets out a program of field work designed to prove the most practical and effective techniques (Section 7).

Determination of in-place coal reserves requires knowledge of the volume of coal and the in-situ bulk density applicable to that volume (Table 1). Assessing the volume is a well understood task, and a reliability factor can be assigned to the results of that assessment. However, to determine the in-situ tonnage, that volume must be multiplied by the in-situ bulk density, a factor that can be difficult to determine with certainty.

When coal has been sampled by coring or bulk sampling, and has been prepared for analysis, it is no longer "in-situ" and the laboratory-determined density or specific gravity may not accurately represent the in-situ value. During sampling and sample preparation, pore fluids are lost (both water and gases), and extraneous materials may be added (drilling mud in coring and out-of-seam material in bulk samples), thus altering the nature of the sample. Uncertainty in the in-situ density introduces uncertainty into the in-situ tonnage assessment, which in turn can affect the assessment of run-of-mine tonnages and clean product tonnages.

In conducting this study, Norwest has been in contact with a variety of companies, organizations and individuals in the Western Canadian coal industry. These people and companies have been kind enough to provide information on their current practices, and a few were able to provide hard data documenting problems in density determination.

Published information has also been reviewed for this study, and some pertinent data is used in this report. Relevant publications are listed in Section 9. Two of the more difficult-to-obtain papers are included in Appendix A.

TABLE 1
DEFINITION OF TERMS

Density The ratio of the mass of a material to its volume (grams per cubic centimetre, tonnes per cubic metre, etc.)

True Density

The density of a material excluding any porosity.

Apparent Density

The density of a material including its inherent porosity and fluids.

In-situ Bulk Density

Density in place, including inherent porosity, fracture porosity, and the fluids in both types of porosity.

Specific Gravity

The ratio of the density of a material to the density of a standard (usually water).

True Specific Gravity

The specific gravity of a material excluding any porosity.

Apparent Specific Gravity

The specific gravity of a material including its inherent porosity.

SECTION 2

PROBLEMS IN DENSITY DETERMINATION

Coal is a complex heterogenous material. In order to understand the problem of determining an appropriate value for in-situ density, it is necessary to understand the structure, and particularly the porosity, of natural coal.

Natural coal may be considered to consist of three fractions:

- pure coal;
- mineral matter; and
- porosity containing water and/or gasses.

Generally the first two fractions receive a great deal of attention from coal mine operators, explorationists, and researchers, while the third is sometimes neglected. For example, in the study of Irvine et al. (1978) on the coal resources of southern Saskatchewan, a great deal of discussion is devoted to the determination of seam thicknesses and coal volumes, but a single density value is used without explanation to convert the volumes to tonnages (p. 105).

In a report for the Electric Power Research Institute on estimation of uncertainty in coal resources, Tewalt et al. (1983, p.3) mention "uncertainty in specific gravity determination" as a source of error. They point out that specific gravities for Texas Wilcox lignite range from 1.21 to 1.62, and that use of an incorrect value can lead to large errors in tonnage, but they give no advice on selection of an appropriate value.

In the study of Dyck et al. (1980), on southern Saskatchewan, true densities (determined on samples ground to -200 mesh) were used to convert volumes to tonnages (p.34). Those values were "considered at best to be approximations of the lignite samples as received at the laboratory and of the density of the lignite in place which is the value required to estimate the tonnage of the coal in place". Using that study as a general example, the questions that arise are:

- is that assumption valid?
- what is the possible magnitude of error?
- what other methods are being used?

The validity of the assumption and the magnitude of error are controlled by the inherent porosity of the coal and the size distribution of the pores (Secton 3), and the amount of fracture porosity (Section 4).

SECTION 3

THE ROLE OF INHERENT POROSITY

There are two general types of porosity in coal. Inherent porosity exists within and between the coal macerals and ash minerals. Fracture porosity (Section 4) is superimposed on the coal as cleats and sheared zones.

Both types of porosity contain fluids in the free and adsorbed state, most commonly methane and water. The ratio of water to gas depends upon the local geologic history.

3.1 PORE SIZE

The inherent pores in coal are usually classified by size:

- macropores (diameter greater than 200 nm);
- transitional pores (1.6 to 200 nm); and
- micropores (diameter less than 1.6 nm).

The percentage of inherent porosity and the size distribution of pores changes with coal rank, but the relationship between rank, porosity and pore size is not clear cut. The work of Parkash et al. (1984) on Alberta subbituminous coals (Figure 1) shows little or no relationship between porosity and rank (expressed as carbon content). Older work by King and Wilkins (1944) found a reasonably distinct trend in high-rank British coals (Figure 2). The latter trend appears to reflect the changes that occur during the later stages of coalification. Low-rank coals have an open structure with an extended system of coarse pores, which disappears gradually as rank increases. During the late stages of coalification, a new system of flat pores forms between hydrocarbon lamellae

(Anthracite Structure) which would account for the final increase in porosity shown by Figure 2.

Grinding a coal sample destroys a part of the inherent porosity, depending upon the final size attained and the sizes of the pores. Parkash (1985) ground coal samples to -60 mesh to measure "porosity-free" true density values. ASTM recommends grinding to -200 mesh in ASTM D 167-73 (1979) "Specific Gravity of Lump Coke". That standard describes how to measure "apparent specific gravity" (i.e., including porosity) from lumps of coke; how to measure "true specific gravity" (i.e., without porosity) from powdered, -200 mesh coke; and how to calculate porosity from the difference between those values. Because ASTM does not offer any similar standard for coal, some laboratories use the ASTM coke standard (Dyck et al., 1980, p. 34).

Pore size is important because sample preparation has a significant impact only on the macropores; the transitional pores and micropores are small enough to survive ordinary grinding and screening. The top size for transitional pores is 200 nm, while the screen openings for -60 mesh and -200 mesh are approximately 250 000 nm and 75 000 nm respectively. An understanding of pore size distribution is therefore necessary for estimating the effect of sample preparation on density values.

Data from Saskatchewan Power Corp. clearly demonstrate that coarse porosity is very significant in Saskatchewan lignites (Section 3.2). The question is whether coarse porosity is significant in higher rank coals. Studies by Fording Coal Limited, Gulf Canada Corporation, the Parkash study, and other reports indicate that coarse porosity may not be

significant in subbituminous and higher rank coals. However, because of differences in sampling, sample preparation and analysis techniques, it may not be valid to compare the data from those different studies. Norwest therefore recommends that coal mine operators perform a small study like the Saskatchewan Power or Fording studies, to determine whether their coals are sensitive to sample preparation and analysis techniques.

3.2 AVAILABLE POROSITY DATA

If we assume that there is no fracture porosity then the "apparent density" values (on an as-received basis) would closely approximate the in-situ bulk density of the coal. In porous coals, however, the "true" densities could be too high by 20% or more.

The available data on inherent porosity are shown on Tables 2 to 6. Data for which rank (fixed carbon) values are available are plotted on Figure 4. The amount of data is limited because porosity is not usually determined during coal analysis; neither are both true[1] and apparent density, from which porosity can be calculated (from ASTM D 167, Porosity = 100 - 100 (Apparent Density/True Density)).

The data provided by Saskatchewan Power Corporation are very significant for coal mine operators. They represent 28 lignites and carbonaceous materials from a Saskatchewan

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1. For the purposes of this discussion, "true density" is assumed to be equivalent to specific gravity determined on crushed or powdered coal by routine laboratory procedures. As discussed in Section 3.1, such samples will, in fact, still contain significant porosity in the coal particles.

deposit. The porosities (calculated by the ASTM formula) range from 1.4 to 25.5% (Table 2) and there is no distinct correlation between porosity and fixed carbon (rank) (Figure 3) or ash content. The samples were prepared and analysed by routine laboratory methods, and showed very significant differences between "bulk density" (i.e., apparent density) and "specific gravity" (intended to represent true density). The Saskatchewan study indicates that:

- there is a significant amount of coarse porosity in Saskatchewan lignites;

- a significant amount of that porosity can be destroyed during sample preparation; and

- destruction of that porosity can cause errors in excess of 25% in density values.

Those facts are not surprising, since it is well understood that low-rank coals have an extended system of coarse pores.

Alberta subbituminous coals were studied by Parkash et al. (1984) of the Alberta Research Council. They studied one bulk sample from each of 11 coal deposits (Table 3). Like the Saskatchewan data, the Parkash data show no apparent correlation between porosity and fixed carbon (rank) (Figure 1) or ash content. There is little similarity between the sample preparation and analysis techniques used in those two studies, however, and it may not be valid to compare the results in detail. The Parkash data were determined by highly sophisticated techniques (helium and mercury displacement) designed to include even the smallest micropores. Pore size distribution varied from sample to

sample, but in general, the majority of the porosity appeared to be small enough to survive sample preparation. The Parkash study was designed to evaluate the volume of the smaller pores, to facilitate studies of coal behaviour during utilization, and it is quite possible that the coarsest fraction of the macroporosity was destroyed prior to analysis (details of sample preparation were not specified).

Fording Coal Limited provided data from an Alberta subbituminous coal project, obtained by routine analytical techniques. They concluded:

> "Bulk Density (as determined from core) is slightly lower than S.G. in coal, and becomes substantially lower in carb shale, diverging increasingly in shale rock."

and:

> "Concern that bulk density of coal would be less than the specific gravity (ASTM) is shown to be true, but the difference is quite small. A correction to change specific gravity to the corresponding bulk density would lower tonnage factors roughly 2.5%, with a consequent reduction of 2.5% in reserves."

Stansfield et al. (1927) of the Alberta Research Council presented data for higher rank Alberta coals (Appendix A). Their data indicate little difference between true and apparent density for those coals, but as Dr. S. K. Chakrabartty of the Research Council pointed out in a telephone interview, analytical methods at that time were primitive, and the data should be regarded with caution. The Stansfield data have not been included in Figure 4 because no rank (fixed carbon) data were available for the samples.

A broad range of American coals were analysed by Gan et al. (1972). Using sophisticated techniques, they found significant differentiates between apparent and true densities (Table 4), and measured open porosities ranging from 4.1 to 23.2% (their measured porosities differ slightly from porosities calculated from the density data). The Gan porosities show a general tendency to decrease with rank (fixed carbon) (Figure 4). Pore size distribution was not determined.

Toda (1972) analysed a broad range of coals from Japan and elsewhere (Table 5) using sophisticated techniques. He differences between apparent and true densities. The Toda samples were chosen for low ash content (5% or less), and all have porosities of less than 10%. The Toda porosities show a vague tendency to increase with rank (Figure 4). The pore size distribution was not determined.

Nelson et al. (1980) published data from a variety of coals from unspecified deposits (probably American). Like Parkash, Gan, and Toda, they used highly sophisticated analytical techniques. They found significant differences between apparent and true densities (Table 6), with calculated porosities ranging from 2.04 to 15.88%. The Nelson porosities show a general tendency to decrease with rank (Figure 4).

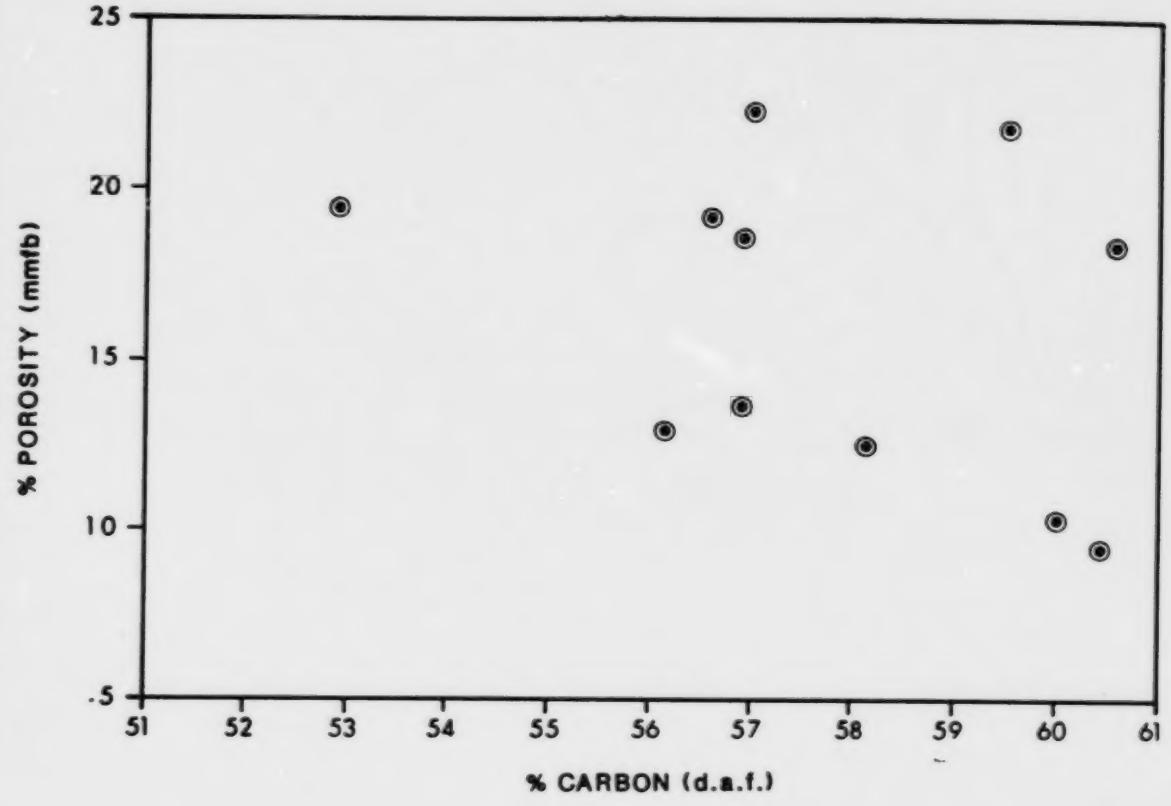
King and Wilkins (1944) published data from British high-rank coals (Figure 2 and Appendix A). Unlike the other reports, the King and Wilkins data show a distinct relationship between porosity and rank (compare Figures 2 and 4). The reason for this is not apparent, but the King and Wilkins

data should probably be regarded with caution, because in their report contradictions exist within conclusions reached, and between different presentations of data.

Gulf Canada Corporation has obtained bulk density and true density (specific gravity) data for a small number of anthracite samples from northern British Columbia. The differences between bulk and true density are so small (0.00 to 0.04 gm/cc) that they may be less than the limits of laboratory accuracy. In fact, half the samples had identical bulk and true density values, and some of the others had bulk density values slightly greater than the true density.

A comparison of all of the data is rather dangerous, because there are major differences in sampling and analytical techniques. An examination of Figure 4 reveals no similarity between the different groups of data, and no overall trend.

It must also be noted, however, that regardless of the sampling and analytical technique, there are no strong trends developed between porosity and rank or porosity and ash (with the exception of the King and Wilkins (1944) data). This observation alone points out the dangers of making assumptions about porosity (or moisture) or bulk density for a particular coal seam, deposit, or rank.



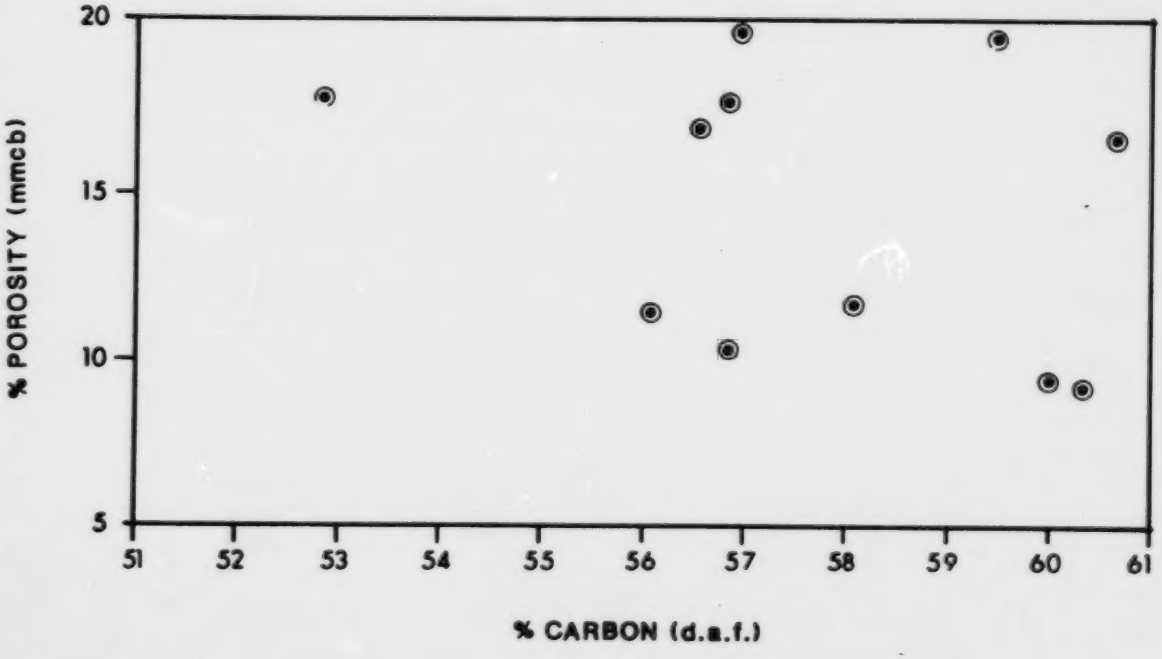


Figure 1 Porosity Data From Alberta Subbituminous Coals (From Parkash et al, 1984).

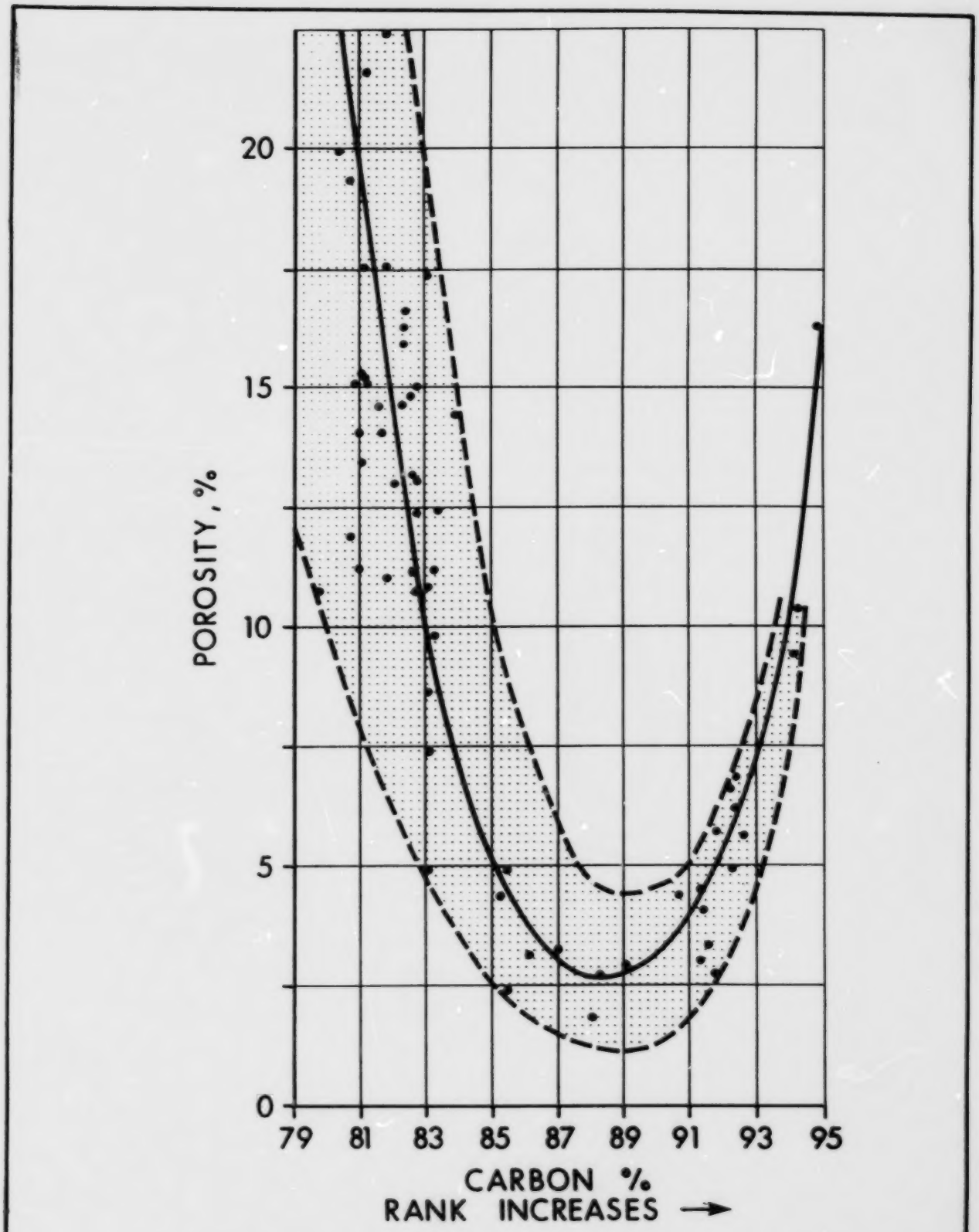


Figure 2 Porosity Data from British High-Rank Coals

(From King and Wilkins, 1944).

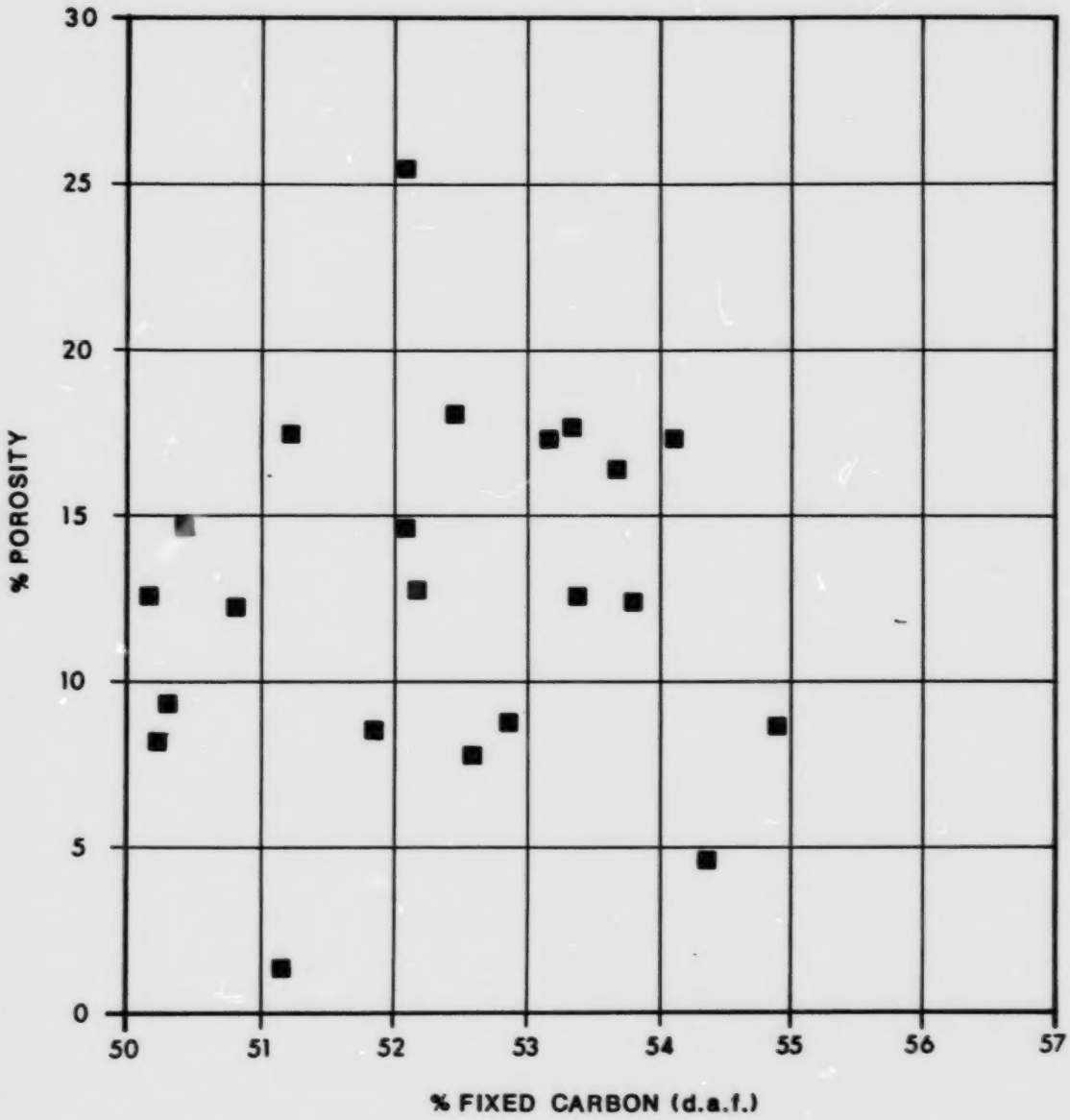


Figure 3 Porosity Data From Saskatchewan Lignites.

(From Saskatchewan Power Corp.)

Resource Consultants Ltd

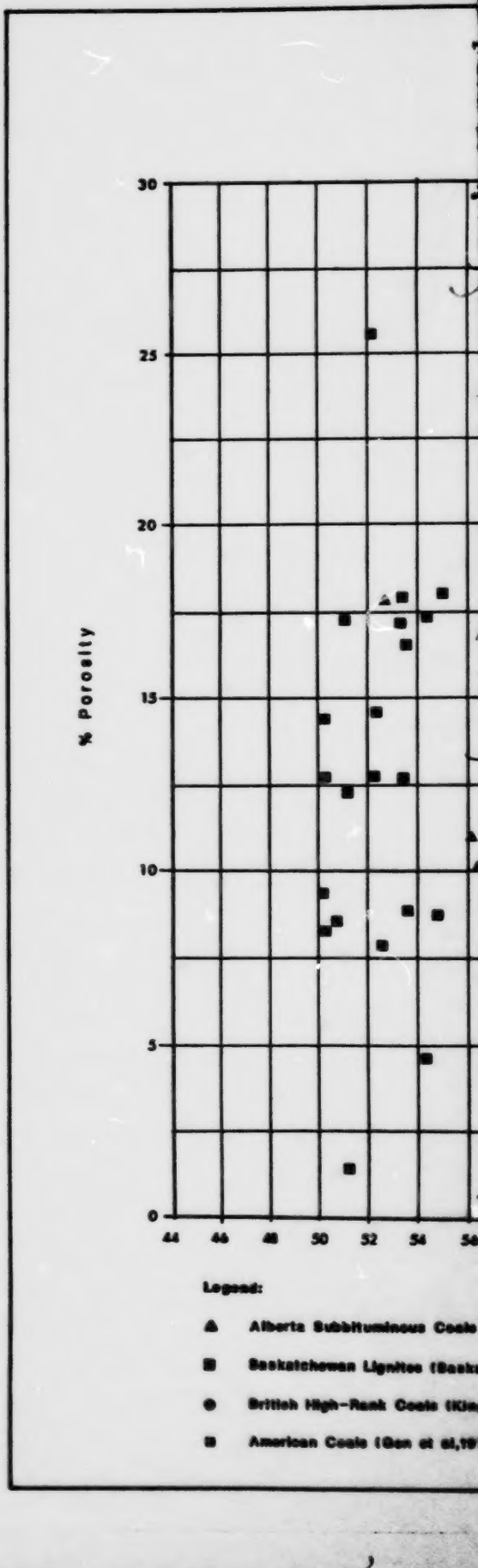
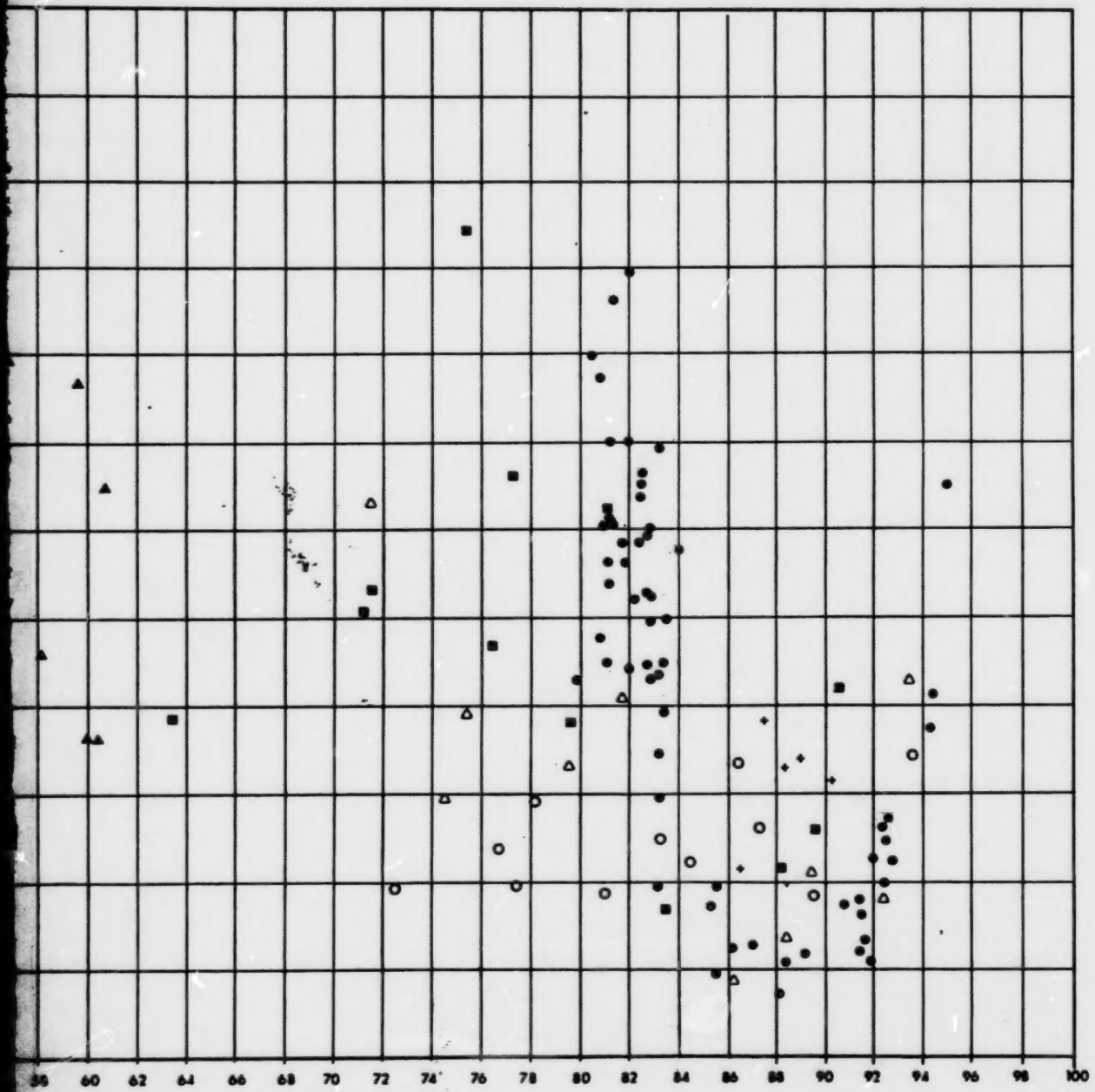

% Porosity
30
25
20
15
10
5
0
44
46
48
50
52
54
Legend:
Alberta Subbituminous Coals
Saskatchewan Lignites (Saska
British High-Rank Coals (Kis
American Coals (Gan et al,19

Figure 4 Summary of Porosity Data.



...kash et al,1984)
...wan Power Corp.)
... Wilkins,1944)
○ Japanese Coals (Toda, 1972)
◆ Miscellaneous Coals (Toda, 1972)
△ Unspecified Coals (Nelson et al, 1980)

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TABLE 2

DATA FROM SASKATCHEWAN LIGNITES

Sample No.	Specific Gravity	Bulk Density	Inherent Porosity (%)	Fixed Carbon (%d.a.f)	Ash (%d.b.)
1	1.58	1.32	16.46	53.70	15.2
2	1.50	1.23	18.00	52.46	12.7
3	1.50	1.31	12.67	53.79	11.7
4	1.41	1.30	7.80	52.63	6.7
5	1.45	1.19	17.93	53.34	7.2
6	1.61	1.20	25.47	52.01	32.7
7	1.85	1.22	34.05	45.85	54.2*
8	1.59	1.45	8.80	54.85	19.6
9	1.50	1.31	12.67	50.18	18.9
10	2.39	1.68	29.71	20.12	83.1*
11	1.57	1.34	14.65	52.12	17.5
12	1.57	1.30	17.20	51.25	20.2
13	1.45	1.32	8.97	52.85	10.5
14	2.30	1.88	18.26	23.12	81.4*
15	1.88	1.54	18.09	44.63	52.5*
16	1.63	1.35	17.18	53.15	22.3
17	1.47	1.40	4.76	54.36	10.6
18	1.51	1.29	14.57	50.40	13.3
19	1.42	1.29	9.15	50.27	8.5
20	1.49	1.31	12.08	51.05	14.4
21	1.44	1.42	1.39	51.17	10.1
22	1.61	1.33	17.39	54.13	17.6
23	1.55	1.35	12.90	52.19	20.1
24	2.70	2.14	20.74	2.22	95.5*
25	2.77	1.98	28.52	0.83	87.9*
26	1.51	1.32	12.58	53.39	12.9
27	1.49	1.37	8.05	50.25	18.6
28	1.41	1.29	8.51	51.81	11.6

* High ash; not graphed

Specific Gravity was assumed to represent True Density, Bulk Density was assumed to represent Apparent Density, and Porosity was calculated according to the formula:

$$\text{Porosity} = 100 - 100\ (\text{Apparent Density}/\text{True Density})$$

TABLE 3

DATA FROM ALBERTA SUBBITUMINOUS COALS

Sample	True Density (g/cm^3)	Apparent Density (g/cm^3)	Inherent Porosity (%)	Fixed Carbon (% d.a.f.)	Ash (% d.b.)
Smoky Tower	1.545	1.284	16.89	56.6	20.0
Fox Creek	1.555	1.412	9.20	60.0	17.0
Judy Creek	1.561	1.262	19.16	59.5	16.0
Egg Lake	1.537	1.382	10.08	56.2	14.6
Highvale	1.511	1.375	9.00	60.4	10.7
Tofield	1.592	1.416	11.06	56.2	24.4
Ardley	1.583	1.324	16.36	60.7	20.0
Vesta	1.487	1.316	11.50	58.1	12.2
Sheerness	1.470	1.212	17.55	56.8	10.9
Blackfoot	1.550	1.241	19.94	57.0	19.4
Bow City	1.453	1.192	17.83	52.9	13.7

From Tables 7 and 8 in: Parkash, S., Chakrabartty, S.K. and du Plessis (1984), Porosity in Alberta subbituminous coals; Alberta Research Council, Coal Report 84-2, 14 pages.

TABLE 4

DATA FROM AMERICAN COALS

Sample	State	True Density (g/cm^3)	Apparent Density (g/cm^3)	Open Porosity (%)*	Fixed Carbon (% d.a.f.)
80	PA	1.67	1.51	10.4	90.8
127	PA	1.38	1.29	6.5	89.5
135	AL	1.36	1.29	5.3	88.3
4	KY	1.30	1.25	4.1	83.8
105A	IN	1.35	1.15	15.5	81.3
RAND	IN	1.36	1.24	9.5	79.9
26	IL	1.41	1.19	16.7	77.2
197	TX	1.49	1.33	11.9	76.5
190	IL	1.38	1.07	23.2	75.5
141	TX	1.42	1.24	13.3	71.7
87	ND	1.46	1.28	12.8	71.2
89	ND	1.55	1.41	9.6	63.3

From Tables 1 and 3 in: Gan, H., Nandi, S.P. and Walker, P.L., Jr. (1972), Nature of the porosity in American coals; Fuel, Vol. 51, p. 272-277.

* As determined by Gan et al.

TABLE 5

DATA FROM JAPANESE AND OTHER COALS

Sample	True Density (g/cm^3)	Apparent Density (g/cm^3)	Inherent Porosity (%)*	Fixed Carbon (% d.a.f.)	Ash (% d.b.)
Tempoku	1.390	1.323	4.82	72.7	4.7
Chikubetsu	1.313	1.235	5.94	76.8	3.3
Taiheiyo	1.308	1.243	4.97	77.8	5.0
Kashima	1.322	1.225	7.34	78.1	4.1
Takamatsu	1.322	1.264	4.39	79.8	2.4
Bibai	1.300	1.238	4.77	81.1	3.4
Akabira	1.288	1.210	6.06	83.4	1.2
Miike	1.294	1.221	5.64	84.5	3.6
Yubari	1.293	1.187	8.20	86.2	2.4
Hashima	1.303	1.220	6.37	87.2	2.2
Nishikawachi	1.324	1.261	4.76	89.8	2.7
Omine	1.502	1.373	8.59	93.7	4.1
Southern Bell	1.309	1.238	5.42	86.6	1.4
Moura	1.328	1.200	9.64	87.6	2.3
Michel	1.323	1.217	8.01	88.4	1.8
New River	1.331	1.224	8.04	89.0	1.5
Itmann	1.366	1.258	7.91	90.7	2.4

From Table 1 in: Toda, Y. (1972), Densities of coals measured with various liquids; Fuel, Vol. 51, p. 108-112.

* Porosity = 100 - 100 (Apparent Density/True Density)

TABLE 6

DATA FROM UNSPECIFIED COALS

Sample	True Density (g/cm^3)	Apparent Density (g/cm^3)	Inherent Porosity (%)*	Fixed Carbon (% dmmf)	Mineral Matter (% d.b.)
177	1.598	1.425	10.83	93.59	4.95
85	1.449	1.382	4.62	92.36	9.54
318	1.372	1.301	5.17	89.51	6.52
254W	1.342	1.281	3.65	88.04	6.91
268	1.320	1.293	2.04	86.50	5.52
223	1.323	1.188	10.20	81.92	4.56
212	1.344	1.234	8.18	79.33	3.05
248	1.363	1.229	9.83	75.44	3.34
242	1.381	1.279	7.38	74.45	6.72
246	1.442	1.213	15.88	71.52	10.99

From Tables 1 and 2 in: Nelson, J.R., Mahajan, O.P. and Walker, P.L., Jr. (1980), Measurement of swelling of coals in organic liquids: a new approach; Fuel, Vol. 59, p. 831-837.

* Porosity = 100 - 100 (Apparent Density/True Density)

SECTION 4

FRACTURE POROSITY

Fracture porosity is mainly a function of the tectonic history of a coal deposit and can be highly variable across any given coal property. Coal at mineable depths always exhibits some degree of fracture porosity, most commonly as cleats. The permeability of coal is mainly a function of its fracture porosity.

Shearing greatly increases the fracture porosities in some of the Foothills and Mountain coal seams. Extreme examples may be seen in the tectonically thickened deposits (Coal Valley, Coal Mountain, Tent Mountain, Grassy Mountain, Vicary, etc.), where the coal has a finely granulated to flakey texture, with intergranular or inter-flake porosity.

Fracture porosity adds its effect to that of the inherent porosity. Unfortunately, it is practically impossible to obtain a sample containing undisturbed fracture porosity. Unless the distribution of fractures (cleats and sheared zones) is quite dense and regular, a core may not represent an average sample of the fracture frequency. Additional fractures may be created by the drilling process or by the relief of in-situ stresses and pressures, and the pre-existing fractures may expand. In addition, because of the high permeabilities associated with fracture porosities, their natural fluids may be lost and drilling fluids may be added. Because of these sampling problems, fracture porosity must be studied in-situ, using either downhole geophysics (Section 5.3.4), or possibly by aquifer analysis techniques.

Fracture porosity is of great importance in conventional oil and gas production, enhanced recovery programs, groundwater production, and hazardous waste disposal, as well as in coal mining where fracture porosity is a major conductor of water and gas. However, no truly effective method for evaluating fracture porosity, either in-situ or by coring, has yet been developed. A variety of assumptions must be made with any approach, and the results have fairly high uncertainties.

No data have been found regarding the fracture porosity of coal, although there are a few studies of coal seam aquifers (e.g., Rehm et al., 1982; C. Sauveplane, Alberta Research Council) which deal with determination of flow parameters. The range of fracture porosities in Western Canadian coals is not known.

Qualitatively, it is known that fracture porosity can be quite significant in sheared coal. The Coal Mountain (Byron Creek) deposit is an extreme example. The coal has a flakey, almost schistose texture with very high inter-flake porosities and permeabilities. Massive drilling fluid losses into the coal occur even with sophisticated and expensive drilling muds, making it nearly impossible to recover meaningful core samples. Because of this, reverse circulation drilling is usually used at the Byron Creek mine, but there are still some problems with fluid loss (and gain) from the very porous coal.

SECTION 5

GEOPHYSICAL LOGGING

Downhole geophysics offers interesting possibilities for the measurement of bulk density in-situ. Geophysical techniques avoid the sampling and sample preparation techniques desribed in Sections 3 and 4, but there are problems with borehole effects, calibration and interpretation instead.

Geophysical logging techniques are not currently used to their maximum potential in the Western Canadian coal industry, despite the technological advances that became available during the late 1970's in response to the world coal boom. At that time, the major contractors had developed density tools with source-detector spacings of 15 cm and less. Focused resistivity tools were available with resolutions of 5 cm or less. Multiple-detector sonic tools were available in slim-hole format, and at least one contractor had developed an interesting high-resolution compensated neutron tool for coal (Reeves, 1978, p. 485).

Several problems have emerged regarding the application of geophysical logging to the determination of coal quality and in-situ coal density:

- availability and cost of logging services;
- calibration and quality of logs; and
- interpretation of geophysical logging data.

Some of these problems were apparent during the 1970's; others are unique to the present economic climate.

5.1 AVAILABILITY AND COST OF LOGGING SERVICES

The falling price of coal during the 1980's has had a very noticable impact on this particular problem. Many contractors have been forced to lay off staff and significantly reduce prices. Others have refused to reduce prices (thus becoming unaffordable to most coal operators), and have turned to other markets. As an economy measure, mining companies have been buying only the most basic and inexpensive logging services. There has also been a growing tendency for mining companies to own and operate their own equipment.

In general, many of the high-resolution tools of the late 1970's are no longer as easily available. Some of the equipment is no longer in Canada. In many cases the equipment has been sitting in storage and has to be retrieved, dusted off and recalibrated before it can be used.

5.2 QUALITY AND CALIBRATION OF DENSITY LOGS

Calibration of density logging tools is particularly difficult because it is difficult to manufacture homogeneous, unflawed standards in the range from 1.0 to 2.0 g/cm^3. The tool response is not linear, so a series of standards within that density range is required to adequately define the response curve for each tool. Some of the major contractors have spent a lot of time and money manufacturing their own private density standards.

Any individual density sonde, regardless of its manufacturer, has its own peculiarities and must be calibrated after major repairs or when its source is changed. Reproducibility can

be maintained in the field by simple tests, usually a one-point normalization using a large tank of clean water to check one point on the response curve. Sometimes two points are used, the second being provided by a metal sleeve that fits over the sonde.

It is not very easy for coal professionals to judge the contractors' density calibration claims, or to be certain that mine-owned equipment is well calibrated. During the mid-1970's the Alberta Research Council made a comparison study of logs produced by four logging contractors from a single test-hole near Hussar, Alberta (Leduc, 1977). The objective was to compare cost, logging time, quality of product and equipment, but the role of government in evaluating logging services proved controversial. The report came to no firm conclusions and was never made available to the public.

A public calibration facility provided and maintained by a government agency would allow interested parties to make their own comparisons and draw their own conclusions, whether they were choosing contractors, purchasing equipment, conducting their own research, or simply maintaining their existing equipment. A calibration facility is under construction at the Institute of Sedimentary and Petroleum Geology in Calgary (Killeen et al., 1984), but progress has been very slow to date.

With the growing trend toward mine-owned equipment, the need for a public calibration facility is increasing. At present, some mining companies keep a drillhole open that they use as their own standard. They log it regularly to check their own

equipment, or have contractors log it to demonstrate their equipment and services.

5.3 INTERPRETATION OF LOG DATA

Once the coal professional has overcome the above two problems and obtained high-quality logs, the question is what to do with them. The major slim-hole contractors developed coal quality interpretation procedures during the 1970's, but their research and testing programs have slowed or been abandoned during the 1980's. None of the methods were ever fully tested by operators in Western Canada, and to Norwest's knowledge, none are in use at present by Canadian operators. While Norwest is not endorsing any particular method, we feel that operators should attempt to make more use of log-derived data, either through techniques offered by contractors, or by developing their own techniques. Since most of today's mines use computers to keep track of everything from payroll to truck parts, they already have the hardware needed to work with log data, which are available from all of the major contractors in suitable digital formats.

The major contractors put a great deal of effort into developing methods for using log data to characterize coal as a three-phase system consisting of a pure coal component, a pure mineral matter component, and a water component. Depending on the individual method, the water component may include water in both the inherent porosity and fracture

porosity, within the coal or both coal and ash fractions. Presumably complete water saturation is assumed.[2]

Although a coal-water-ash type of approach is necessary to completely define coal quality, measurement of in-situ bulk density alone is a much simpler problem. In the absence of serious borehole effects, a well calibrated, high-resolution sidewall density sonde should record accurate in-situ bulk densities representing the contribution of all three components in their respective in-situ proportions.

5.3.1 Lab Data Versus Log Data

Whether one is using log density values alone, or a complete coal-water-ash approach, the results are not directly equivalent to laboratory-derived values because there are differences in the water content between in-situ coal and a laboratory sample. Depending upon how the sample is handled (i.e., upon whether it is finely ground or not), the laboratory results may or may not include the water within the inherent porosity, but in any event they include little if any of the fracture porosity and its water. The geophysical data represent the in-situ condition; the laboratory data do not.

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[2] A weakness of geophysical coal-water-ash approaches in general may be their assumption of complete water saturation. Depending upon geological setting, a seam may be dry or partially drained. Further, some of the very small pores that develop as rank increases tend to be filled with adsorbed gasses that were produced during coalification. Because of the very low permeabilities associated with those pores, they tend not to become filled with liquid water.

Since laboratory data have been available for longer than geophysical log data, the laboratory data are the accepted standard that mines, buyers and investors use. For this reason, Edwards and Banks (1978, p.7) carefully explained how to convert the results of their coal-water-ash method to laboratory-equivalent data by adjusting the water content (and the volatilized portion of the mineral matter fraction). It can be argued that, if properly understood, the in-situ geophysical data can be more meaningful than laboratory data. However, the fact remains that, throughout the world, laboratory data are the standard, and it is probable that the apparent difference between geophysical log data and laboratory data is the reason for the reluctance of industry to rely on geophysical log data.

Because of the effect of porosity (particularly fracture porosity), in-situ bulk densities from geophysical logs are smaller (lighter) than those measured by laboratories. Their use in reserve calculations would thus result in smaller in-situ reserve figures (and higher overburden ratios), hence a reluctance by industry to use them, without adjusting them to match laboratory values, is understandable. However, it is true none the less, that a significant percentage of any coal seam in-situ is in fact water and/or gas. It is this fact that has led some researchers to speculate that in-situ coal reserves have been consistantly overestimated. That statement is in general difficult to either prove or refute. The important question may be whether the water and gas content are adequately compensated for in conversions from in-situ reserves to run-of-mine tonnages.

5.3.2 The State of Coal-Water-Ash Methods

Roke has not changed its method significantly since it was published (Edwards and Banks, 1978). The Roke approach is theoretical, based firmly on theoretical and practical work done in the petroleum industry. It uses density and focused resistivity log data. Roke prides itself on the calibration of its density tools, and Roke's focused resistivity sondes are highly sophisticated, seven-electrode devices. One of the practical drawbacks to Roke's approach is that their focused resistivity sondes are long devices that must be run separately from other sondes. Many potential users want to run a single, one-trip combination sonde. Roke's method relies heavily on resistivity data, and smaller resistivity devices that can be included in combination sondes may not be adequate.

The Century method (Norris and Thomas, 1979) has been further refined and tested since Hoffman et al. (1982) was published, but it still works in basically the same way. The development has been done in the United States, particularly in Texas lignites. No one has tried the method in Canada, although Century has been actively seeking an opportunity to demonstrate it. Century's method is an empirical approach, based upon establishing the relationship between the response of a single log, the density log, and laboratory data.

BPB's method has become available since the publication of Hoffman et al. (1982). Similar to the Schlumberger method (Bond et al., 1971), BPB's Coal Seam Evaluation package (described in BPB's current circular on Base Computer Centres, p. 12) determines volumetric percentages of "mineral matter, coal substance and moisture" from density and sonic

log data. In the Schlumberger method, the volumetric percentages are converted to weight percentages by applying density log values.

BPB reports that its method is being used in many coalfields throughout the world, but has met with no interest in Canada. Indeed, it is interesting that although BPB's North American base computing centre is located in Calgary, the vast majority of the work that it handles comes from the United States.

The one fact that all of the contractors definitely agree on is that at present, there is little interest among the Canadian mine operators in any of the highly sophisticated interpretation services that are being offered.

5.3.3 Future Interpretation Possibilities

The possible approaches to coal interpretation have not yet been fully explored. Roke uses density and focused resistivity data; Century uses the density log alone; and BPB and Schlumberger use density and sonic data. It is possible that a three-log approach might be the next step, because a three-phase system (coal, water and ash) could be better defined by three independant input parameters (density, focused resistivity and sonic).

The high-resolution compensated neutron log developed by BPB (Reeves, 1978, p. 485) might also be suitable for use in coal interpretation. BPB ran a log of that type for Crows Nest Resources, and its resolution appeared similar to that of the focused resistivity and density logs. It would be interesting to compare the logs with the analytical data from

that hole. Brom and Driedonks (1981) also used that neutron tool for Shell in Europe. They found a good relationship between volatile matter content and the high-resolution neutron log data (i.e., Hydrogen Index). They felt that they were detecting changes in hydrogen content due to changes in maceral content, but did not mention any effect due to changes in porosity or water content.[3] They felt that focused resistivity logs have the best potential for measuring moisture content. They examined data from low-rank coals in Canada, Indonesia, Germany and Australia, and concluded that "moisture content in-situ can be reliably determined from the new-generation focused electric log, even without specific knowledge of the coal-water salinity, which proved difficult to assess" (Brom and Driedonks, 1981, p. 13).

Downhole gravimeters are another potential source of density-related data, but these are still in a fairly experimental stage of development. Robbins (1979) reported the use of a borehole gravimeter to determine in-situ denisty in a Colorado lignite. He found differences between the gravity-determined densities and the gamma-gamma densities within the lignite, but not in the clastic sediments. The gamma-gamma densities were 0.2 to 0.3 g/cm^3 greater. He believed the gravity data were correct, and attributed the differences to errors in the gamma-gamma data caused by (1) inadequate Z/A corrections and (2) borehole effects. His paper leaves many questions unanswered, principally because (1) the density and

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3. The data from the Saskatchewan lignites indicate that significant variations in porosity and water content are likely. Theoretically these variations should be reflected by changes in the Hydrogen Index. This aspect warrants more research.

gravity logs were made at different times and by different people, and (2) no core data were available from the hole, although data from "nearby samples" were used (on p.14, such data were used to calculate a porosity of 40 to 53% for the lignite). The similarities and differences between the gravity and gamma-gamma data are interesting, however, and indicate that a more rigorous study, with core data and a full suite of logs, could provide new insight into in-situ density determination.

5.3.4 Fracture Determination

Fracture porosity is of great importance to the petroleum industry, as well as to coal, hydrogeology and recently, to hazardous waste disposal, so a great deal of research has been devoted to the subject. Logging contractors, geotechnical engineers and laboratory specialists tend to agree that there is no single method that is universally effective for the evaluation of fracture porosity, either by geophysical logging or coring. Sonic logs, and even downhole radar, have been tried and are helpful under some circumstances, but for use in coal, the density log may be the most helpful. If the apparent density (i.e., including inherent porosity) of the coal is known from core samples, then differences between the laboratory-determined density and the geophysical density should be a function of the degree of fracture porosity.

Sheared zones can be identified because they produce anomalous responses on density and focused resistivity logs. Unfortunately, it is usually difficult to obtain open-hole logs in heavily sheared coal.

SECTION 6

CURRENT PRACTICES IN DENSITY DETERMINATION

6.1 LIGNITES AND SUB-BITUMINOUS COALS

Some operators producing coal of these ranks are quite aware of reserve estimating problems associated with variations in pore fluids within a reserve, and between coal in the ground and plant feed coal. Certainly these coals have the greatest inherent porosity and the effect of porosity and moisture are reflected in the differences between bulk density and specific gravity.

Saskatchewan Power Corporation and Fording Coal Ltd. both prefer to use bulk density information from drill core and other samples whenever possible, at least in the planning stages for mine development. Both prefer to use laboratory bulk density values determined on an "as received" basis, and both realize that while even this procedure is not entirely correct, it provides a much better estimation than specific gravity.

Other operators producing lignite or sub-bituminous coals either did not respond to enquiries during the study, or reported that they use either laboratory determined specific gravity, bulk sample data, or a combination of those techniques.

Operators reported that isolated areas of fractured coal occur in their reserve areas but that they were not given special treatment in reserve estimations.

6.2 BITUMINOUS COALS AND ANTHRACITE

A variety of responses were received from operators producing bituminous coals. Most mines use techniques that evolved during the course of mining operations, and most operators are comfortable with the level of confidence they have in their reserve estimates. No particular techniques were favored by operators in any particular rank of coal, and most operators have tried or are presently using more than one technique.

The techniques used to determine in situ bulk density for reserve estimation in higher rank coals as reported by the operators include:

- Bulk samples
- Borehole geophysical logs
- Laboratory determined specific gravity data
- Lump coal bulk (relative) density data
- Historical average values

Bulk Samples

Many operators have derived bulk density values as a result of bulk sampling activities, and this method was commonly mentioned as being in addition to, or in support of other techniques. No operators identified it as the primary technique used to determine in situ bulk density values.

Borehole Geophysical Logs

Most operators have used or are using borehole geophysical logs in conjuntion with other data to arrive at density

values used to estimate in situ reserves. One mountain coal operator reported that a combination of borehole geophysics and bulk samples was the preferred techniques.

Specific Gravity Data

The use of laboratory derived specific gravity data, and regression analysis equations based on that data, for in situ reserve estimation was the most widely reported practice. For two operations the use of specific gravity data was reported to be the primary or the only method used. Most operators reported that this technique was (or has been) used in conjunction with other information - borehole geophysics or bulk sampling.

Lump Coal Bulk Density

Two operators reported that relative density values, determined on lumps of coal or on drill core samples, were used to convert coal volumes to in situ tonnages.

Historical Average Values

Many operators reported, in discussion, that on a day to day basis tonnage factors based on mining history were important in determining reserves.

Two operators identified variations in porosity (and moisture) as a significant concern in reserve estimating, particularly as it relates to sheared or fractured coal. One of these operators has developed an equation to determine in situ density, and although the calculation relies on estimates of in situ moisture (recognized as a problem) it is

a example of another approach being taken to identify a reliable density value for in situ reserve estimation.

SECTION 7

PROPOSED FIELD TESTING PROGRAM

The most practical information on coal density determination has come from the coal mine operators themselves. Studies like Parkash et al (1984) use sophisticated techniques designed to measure transitional and microporosity, and it is difficult to isolate the effect of the coarse porosity that is significant to reserve calculation. A field testing program designed to evaluate the problem from the mine operators' point of view, for a variety of coal ranks, would help to resolve the practical questions about density determination. A number of coal mine operators and explorationists have expressed interest in such a program, and would be willing to participate if they are conducting drilling programs at the time of the study.

Table 7 outlines a proposed field testing program. Highlights of the program would be as follows:

1. Determine the Effect of Inherent Porosity on Density and Specific Gravity

Using a lump sample or core sample, have a laboratory determine bulk (apparent) density. Then have them determine density (specific gravity) when the sample is ground to progressively smaller sizes (-20, -60, -100, -200 mesh). Graph the results (sample, or sieve size versus density and specific gravity). The shape of the curve will be controlled by the percentages of coarser pores, which is in part a function of rank.

Norwest expects that the curves will have different shapes in different coals. Where the curves are fairly flat, sample preparation is not sensitive. Where there is a high degree of curvature (i.e., a large change in specific gravity with grinding), sample preparation must be done with caution.

2. Compare Geophysical and Laboratory Data

Gamma-gamma density will be measured by a well calibrated, high-resolution instrument, using a Z/A correction that is suitable for coal. The results will be compared with the plots above.

Geophysical densities and apparent relative densities should be very similar, except in areas where there is significant fracture porosity, which would result in the geophysical values being lower. Laboratory-determined apparent density should be very similar to in-situ bulk density where fracture porosity is minimal.

3. Determine the Effect of Fracture Porosity

This will be the most difficult aspect of the program, since fracture porosity is always disturbed by sampling, and so must be determined by in-situ tests which can be quite controversial. If there is found to be good correspondence between apparent relative density and geophysical density where fracture porosity is minimal (Step 2 above), then in areas with significant shearing and/or fracturing, the fracture porosity should be represented by the difference between the laboratory apparent density value and the in-situ geophysical density value. This could best be checked in an area where there is a sheared zone within an otherwise fairly

unfractured seam, such as Smoky River. Laboratory and geophysical data could be compared on a ply-by-ply basis across the zone.

4. Benefits

The study would provide a good indication of the degree to which inherent porosity and/or fracture porosity can affect the determination of in-situ bulk density in Western Canada. If it is found that they do have an effect in some areas, operators could perform the simple tests above. By performing the test in Step 1 for representative samples, they could identify whether their coal is sensitive to sample preparation effects. By comparing log and lab data (Step 2 & 3), they could identify areas where fracture porosity has a significant impact on in situ density.

TABLE 7

OUTLINE OF PROPOSED FIELD PROGRAM

Data Collection

1. Core drilling

   - careful coring, very high recovery (no mud if possible)
   - core described on site, in split tube
   - photography of core
   - samples into split plastic tubes, wrapped and waxed

2. Geophysical Logging

   - interested contractors will run their high-resolution density logs, and other logs as they deem appropriate
   - logging will be witnessed by coal geologists

3. Laboratory Analysis

   - bulk density determination on unground core
   - specific gravity determination on decreasing mesh sizes
   - proximate analysis
   - petrography may be desirable

Interpretation

- plot density versus sample preparation
- plot bulk density versus log density
- study relationships between pure coal, moisture, ash, and porosity; as received, dry, m.m.f., etc.
- possibly run geological coal-water-ash analyses
- comparison of results for different coal ranks
- comparison of results in at least one highly fractured/sheared situation.

Conclusions and Recommendations

- will be made after interpretation.

SECTION 8

CONCLUSIONS AND RECOMMENDATIONS

8.1 CONCLUSIONS

Overestimation of reserves can have severe technical and financial implications for a mining operation. If a company realizes that its reserves have been overestimated due to a past misunderstanding of specific gravity and density data (or for any other reason), it must identify the magnitude of any discrepancy in order to fully assess the implications for mine planning. This issue is particularly important for new mine developments in the feasibility, design, and pre-investment stages.

In summary, conclusions reached during this review and assessment are:

1. Data provided by some of the coal mine operations, and other data available in published literature indicate that there can be very significant differences between true and apparent densities in some coals, particularly lignites. Presumably this is due to coarse porosity which is destroyed during the determination of true density (specific gravity). For sub-bituminous and higher rank coals, the sparse data available indicate that the magnitude of the problem is not as extreme, although the data base is insufficient to quantify the problem.

2. In general, the Western Canadian coal industry recognizes that there may, in some cases, be

differences between the specific gravity values reported by laboratory analyses and actual in situ density values for a given coal seam. For most coal deposits the magnitude of the differences are not known, nor is the data base available for operators to properly assess the situation.

3. Those operators who are planning new mine developments expressed the most interest in the problem and were most aware of the implications.

4. Most operators with a sufficiently long production history use techniques for reserve estimation that have evolved during the course of mining operations. These techniques include the use of bulk sample data, various ash-specific gravity and ash-density relationships for specific seams, and the application of one or more correction factors (such as factors for geological confidence, mining, recovery, mining loss, wind loss, moisture corrections, dilution, etc.) These techniques work for operations with sufficient history, although without correct knowledge of in situ reserves we don't know how an operation can correctly assess such factors as mining loss. These factors are, of course, very real, but are very, very difficult to measure.

5. From a technical perspective, it is difficult to estimate the effect of porosity on specific gravity and density because there is so little data available on pore size distribution. The information available indicates that from a practical perspective the coarsest macroporosity is important to reserve

assessments, and it can be evaluated readily with a simple and relatively inexpensive sampling and analytical program.

6. With one exception, all the published and unpublished data on porosity (or specific gravity and bulk density) showed the same result regardless of analytical techniques: There are no significant trends between porosity and rank (fixed carbon) or porosity and ash. This observation alone points out the risks of making assumptions about porosity or bulk density for particular coal seams, deposits or ranks.

7. The evaluation of fracture porosity is an extremely difficult problem which has been the subject of decades of research in the oil industry. In situ geophysical techniques are the most practical approach, because it is not possible to obtain undisturbed core samples, but there is no universally effective method available at present.

8.2 RECOMMENDATIONS

1. Because many mine operators are now beginning to conduct geophysical logging programs with their own equipment the need for a common standard calibration facility is becoming more important. Work on the facility at the Institute of Sedimentary and Petroleum Geology should continue.

2. A field and laboratory testing program, outlined in this report, should be undertaken to obtain the data necessary to adequately assess the implications of

sampling and laboratory techniques on density factors to be used for reserve estimation, and to better assess the effects of fracturing and shearing on in situ bulk density of coal. The program would study the problem of density determination from a mine operator's point of view and would be based on commonly used, readily available techniques, rather than new or particularly sophisticated procedures. In addition mine operators should implement simple and relatively inexpensive studies to determine whether determination of in situ bulk density for their coal is sensitive to sample preparation techniques.

SECTION 9

9. REFERENCES

American Society for Testing and Materials, 1984: 1984 Annual Book of ASTM Standards; Volume 05.05, Gaseous Fuels; Coal and Coke; American Society for Testing and Materials, Philadelphia, Pennsylvania, U.S.A.; 574 pages.

Bond, L.O., Alger, R.P. and Schmidt, A.W., 1971: Well log applications in coal mining and rock mechanics; Transactions of SME, Vol. 250, p. 355-362.

Brom, R.W.C. and Driedonks, F., 1981: Applications of petrophysical logging in the evaluation of coal deposits; Society of Professional Well Log Analysts, Transactions 22nd Annual SPWLA Logging Symposium, Paper KK, 29 pages.

Dyck, J. H., McKenzie, C. T. Tibbetts, T.E. and Whitaker, S.H., 1980: Quality and Occurrence of Coal in Southern Saskatchewan, Canada; Vol. 1, Introduction to Data Acquistion and to Associated Computer Processable Files; Saskatchewan Research Council and CANMET, Energy, Mines and Resources Canada, Rept. No. ERP/ERL 80-84 (TR).

Edwards, K.W. and Banks, K.M., 1978: A theoretical approach to the evaluation of in-situ coal; Canadian Mining and Metallurgical Bulletin, Vol. 71, No. 792, P. 124-131.

Gan, H., Nandi, S.P. and Walker, P.L., Jr., 1972: Nature of the porosity in American coals; Fuel, vol. 51, p. 272-277.

Halker, A., Kuznir, N.J., Mellor, D.W. and Whitworth, K.R., 1982: The synthesis of fracture/strength logs using borehole geophysics - a new geotechnical service; Quarterly Journal of Engineering Geology, Geological Society of London; Vol. 15, p. 15-28.

Halker, A. and Williams, R.G. 1983: A totally digital logging system for coal exploration; Proceedings of the 4th International Coal Exploration Symposium, Sydney, N.S.W., Australia, 15-20 May 1983; G.O. Argall, Jr., Editor, Miller Freeman Publications, San Francisco, U.S.A.

Hoffman, G.L. Jordan, G.R. and Wallis, G.R., 1982: A Geophysical Borehole Logging Handbook for Coal Exploration; Coal Mining Research Corporation, Devon, Alberta; 270 pages.

Irvine, J.A. Whitaker, S.H. and Broughton, P.L., 1978: Coal resources of southern Saskatchewan: a model for evaluation methodology - Part I; Geological Survey of Canada, Economic Geology Report No. 30.

King, J.G. and Wilkins, E.T., 1944: The internal structure of coal; Proceedings, Conference on Ultra-Fine Structure of Coals and Cokes; British Coal Utilization Research Authority, p. 46-56. See Appendix A.

Killeen, P.G., Bernius, G.R., Schock, L. and Mivenifumbo, C.J., 1984: New developments in the GSC borehole geophysics test area and calibration facilities; in Current Research, Part B, Geological Survey of Canada, Paper 84-1B, p. 373-374.

Lavers, B.A. and Smits, L.J.M., 1976: Recent developments in coal petrophysics; Proceedings of the First International Coal Exploration Symposium, London, England, 18-21 May 1976; W.L.G. Muir, Editor; Miller Freeman Publications, Inc., San Francisco, U.S.A., p. 129-152.

Leduc, R.J., 1977: Report on results of comparisons of geophysical logging techniques by representative Alberta firms; Alberta Research Council, unpublished report (part of the 1976 Plains Coal Exploration Program).

Neiswender, C., 1980: Procedure for establishing the slopes and intercepts necessary for in-situ coal quality calculations; Century Geophysical Corporation, Tulsa, Oklahoma, U.S.A., 42 pages.

Nelson, J. R., Mahajan, O.P. and Walker, P.L., Jr., 1980: Measurement of swelling of coals in organic liquids: a new approach; Fuel, vol. 59, p. 831-837.

Norris, J.O. and Thomas, R., 1979: Texas lignite coal quality prediction test; Technical Report 158, Century Geophysical Corporation, Tulsa, Oklahoma, U.S.A., 9 pages.

Norwest Resource Consultants Ltd., 1985: A detailed review and evaluation of methane prediction techniques and their applicability to Canadian coal mines; Department of Supply and Services Canada, D.S.S. File No. 07SQ.23440-5-9008.

Norwest Resource Consultants Ltd., 1984: Water infusion technology for dust control on longwall faces in the Sydney coalfield; Department of Supply and Services Canada, D.S.S. File No. 14SQ23440-4-9102.

Paillet, F.L., 1985: Applications of borehole-acoustic methods in rock mechanics; Proceedings, 26th U.S. Symposium on Rock Mechanics, Rapid City, South Dakota, U.S.A., 26-28 June 1985; E. Ashworth, Editor; p. 207-220.

Paillet, F.L. and White, J.E., 1982: Acoustic modes of propagation in the borehole and their relationship to rock properties; Geophysics, Vol. 47, No. 8, p. 1215 - 1220.

Parkash, S., 1985: True density and elemental composition of subbituminous coals; Fuel, Vol. 64, p. 631-634.

Parkash, S. and Chakrabartty, S.K., 1986: Microporosity in Alberta Plains coals; International Journal of Coal Geology, Vol. 6, p. 55-70.

Parkash, S., Chakrabartty, S.K. and du Plessis, M.P., 1984: Porosity in Alberta subbituminous coals; Alberta Research Council, Coal Report 84-2, 14 pages.

Reeves, D.R., 1981: Coal Interpretation Manual; BPB Instruments Ltd., East Leake, U.K.

Reeves, D.R. 1978: Some improvements and developments in coal wireline logging techniques; Proceedings of the Second International Coal Exploration Symposium, Denver, Colorado, U.S.A., Oct. 1978; G.O. Argall, Editor; Miller Freeman Publications, Inc., San Francisco, U.S.A.; p. 468-489.

Reeves, D.R., 1976: Application of wireline logging techniques to coal exploration; Proceedings of the First International Coal Exploration Symposium, London, England,

18-21 May 1976; W.L.G. Muir, Editor; Miller Freeman Publications, Inc., San Francisco, U.S.A.; p. 112-128.

Rehm, B.W., Moran, S.R. and Groenwold, G.H., 1982: Natural groundwater recharge in an upland area of central North Dakota, U.S.A.; Journal of Hidrology, Vol. 59, p. 293-314.

Robbins, S.L., 1979: Density determination from borehole gravity data from a shallow lignite zone within the Denver Formation near Watkins, Colorado; Society of Professional Well Log Analysts, Transactions 20th Annual SPWLA Logging Symposium, Tulsa, Oklahoma, U.S.A.; Paper JJ, 20 pages.

Romaniuk, A.S. and Naidu, H.G., 1984: Coal Mining in Canada, 1983; CANMET Report 83-20E, 46 pages.

Romaniuk, A.S. and Rushton, H.G., 1985: Canada's coal resources and reserves: an overview. In T. H. Patching (ed.), Coal in Canada; Canadian Institute of Mining and Metallurgy, Special Volume 31, p. 9-20.

Samworth, J.R., 1974: The radiation density log applied to the resolution of thin beds in coal measures; Proceedings of the 3rd European Formation Evaluation Symposium, London, U.K., 14-15 Oct. 1974; Society of Professional Well Log Analysts, London Chapter, Paper R, 11 pages.

Samworth, J.R., 1979: Slimline dual-detector density logging - a semi-theoretical but practical approach to correction and compensation; Proceedings of the 54th Annual Fall Technical Conference and Exhibition of the Society of Petroleum Engineers of AIME, Las Vegas, Nevada, U.S.A., 23-26 Sept.

1979; Society of Petroleum Engineers of AIME, Dallas, Texas, U.S.A., Paper SPE 8365, 8 pages.

Schaefer, J.J. Jr., 1983: Interpretation and use of laboratory data for estimating coal and reserve quality; Proceedings of the 3rd International Coal Testing Conference, Lexington, Kentucky, U.S.A., 24 October 1983.

Schmitz, D., 1984: Interpretation of coal and surrounding strata on the basis of geophysical borehole measurements; Gluckauf Forschung, Vol. 45, No. 4, p. 181-188.

Smith, G.G., in preparation: Theoretical estimation of in-situ-in-bulk density of coal; in preparation, Institute of Sedimentary and Petroleum Geology, Calgary, Alberta; 18 pages.

Smith, S.R., Voorhis, W.M. and Young, J.D., 1981: Coal pile density studies for inventory control; American Institute of Mining Engineers Annual Meeting, Chicago, Illinois, U.S.A., 22 Feb. 1981; 10 pages.

Stansfield, E., Lang, W.A., Sutherland, J.W., Gilbert, K.C. and Zeavin, S., 1927: Specific gravity of coal; Scientific and Industrial Research Council of Alberta, Report No. 22, p. 21 - 23. See Appendix A.

Stine, R.A. (Editor), in preparation: The Drilling, Sampling and Analysis of Coal; ASTM Special Technical Publication, in preparation; American Society for Testing and Materials, Philadelphia, Pennsylvania, U.S.A.; 75 pages.

Tewalt, S.J., Bauer, M.A. Mathew, D., Roberts, M.P., Ayers, W.B., Jr., Barnes, J.W., Kaiser, W.R., 1983: Estimation of uncertainty in coal resources; Electric Power Research Institute, EPRI Report EA-3133, 137 pages.

Toda, Y., 1972: Densities of coals measured with various liquids; Fuel, vol. 51, p. 108 - 112.

Wenk, G.J. and Dickson, B.L., 1981: The gamma-logging calibration facility at the Australian Mineral Development Laboratories; Bulletin of the Australian Society of Exploration Geophysicists, Vol. 12, no. 3, p.1 37-39.

Williamson, I.A., 1967: Coal Mining Geology; Oxford University Press, London, U.K.; 266 pages.

Wright, P. L. and Hernadi, N., 1978: More accurate determination of coal stockpile inventories; The Coal Miner, Dec. 1978, p. 15-17.

van Krevelen, D.W., 1961: Coal: Typology - Chemistry-Physics - Constitution; Elsevier, Amsterdam, The Netherlands, 505 pages.

APPENDIX A

SELECTED PUBLICATIONS

APPENDIX A-1

King, J. G. and Wilkins, E.T., 1944: The internal structure of coal; Proceedings, Conference on Ulta-Fine Structure of Coals and Cokes; British Coal Utilization Research Authority, p. 46-56.

THE INTERNAL STRUCTURE OF COAL

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(Received 12th May, 1945)

DURING 1938 one of us pointed out at a meeting of the Society of Chemical Industry in Newcastle (1) the importance of studying the internal structure of coal in order to obtain a greater insight into its behaviour in industrial processes.

Although our knowledge of the properties of coal has reached the stage where we can recognise readily the gradual change of properties with carbon content, the study of the internal structure of coal has not been pursued actively enough despite the fact that it has been recognised for many years that coal has a micro-porous structure which is different in different types of coal.

During a number of years prior to the War the study of the physical structure of coals had become of special interest at the Fuel Research Station, not so much as a separate programme, but in connection with other researches such as those upon the cleaning of coal by froth flotation processes, the manufacture of active carbon, and the preparation of reactive fuels for the gas producer. Although war-time programmes have delayed progress since 1939, it is of interest to review for the purposes of this Conference the work which has been done, recognising that it is too early yet to draw conclusions except in certain details. Some of the work has already been reported in the Annual Reports of the Fuel Research Board.

The technique used has involved determinations of the heat of wetting, studies of ultimate porosity as measured in several different ways, and other aspects of coal structure.

The Porosity of Coal.

Much of our attention has been concentrated upon the examination of the free space within the coal substance. Our observations support the view that in general coal is interspersed by pores or capillaries of various sizes which give it a sponge-like structure. The diameter and extent of these capillaries is a measure of total internal surface, but their nature largely determines the effect of that surface upon the properties of the coal. The smallest capillaries are capable of becoming filled with condensed vapours, a form of capillary condensation which will not be shown by the larger pores, the latter acquiring a surface film only. The size of the pores in coal therefore presumably determines the accessibility of the internal surfaces and

it may be that while the smallest pores will exert their influence in slow chemical reactions such as those which occur during weathering, the larger capillaries will play the more important part in rapid reactions, possibly including those of combustion. When it becomes possible, therefore, to present a complete picture or analysis of the pore structure of any coal, we shall have gone a long way towards understanding its properties and its behaviour in reactions of different types.

The method of determining the percentage of total free space within porous substances by calculation from their true and apparent specific gravities is well known, but the only application to coal appears to be that published in the Report of the Fuel Research Board (2). In applying this method to coal, porosity was calculated from the true specific gravity of the finely-ground coal and the apparent specific gravity of dust-free coal (over $\frac{1}{72}$ in.) by displacement in mercury.

A second simple method adopted was to impregnate the coal with water, allow it to dry until the surface film of moisture just disappeared and then to calculate the moisture content as a measure of the total volume of the capillaries.

In both cases the methods are applicable to coals of any ash content and although the technique is of the simplest, it is interesting to find that the results are repeatable to a satisfactory extent.

Porosity results obtained in these ways are, of course, not absolute values. In the case of charcoal the observed specific gravity depends partly upon the liquid used. Harkins and Ewing (3) have shown the possibility that this effect is due to the different compressibilities of liquids, and Goldman and Polanyi have concluded (4) that the actual value of the specific gravity is generally less than the observed value. Howard and Hewlett (5), however, after studying various liquids, have concluded that, with certain media, the incomplete penetration of very fine pores may yield low results. Lea (6) has observed a superficial expansion of coal on wetting, which may affect the value, but our results suggest that any error in the porosity figure obtained due to expansion is within the experimental limits of accuracy of the simple methods adopted.

We have calculated the porosity values of a large number of British coals of different rank and have shown these graphically in Figures 1 and 2, plotting the percentage porosity against the rank of the coal expressed in terms both of volatile matter and of carbon. The results should more suitably have been expressed on the basis of pure coal calculated by the method of King, Maries and Crossley (7) but they are expressed in this case on the dry ash-free basis in order to include a larger number of coals for which the mineral matter correction had not been obtained. Owing to the dispersion of the points within the porosity band so obtained it is unlikely that calculation to pure coal would yield a different pattern. This has been checked where possible and found to be so.

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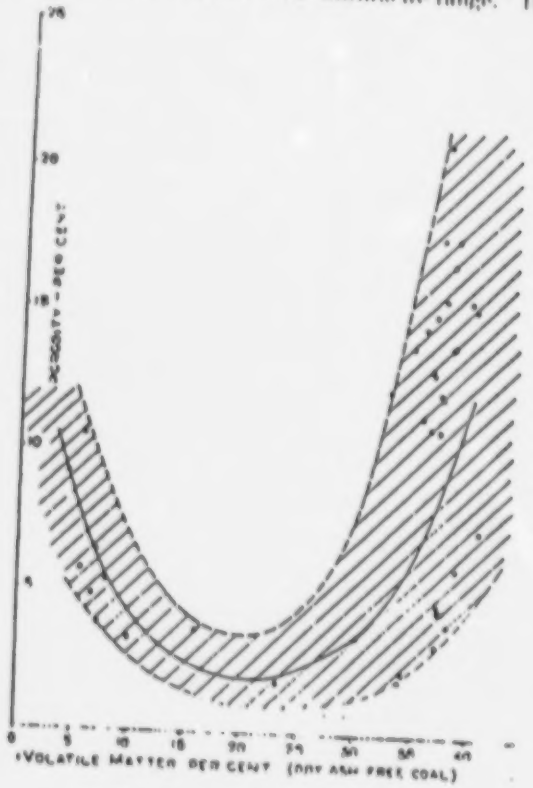
The general trend in these porosity curves is an indication of high porosity at low rank, minimum porosity in the neighbourhood of 89 per cent. carbon or 20 per cent. volatile matter, and a tendency for porosity to increase again in the anthracite range. It was only



VARIATION OF COAL POROSITY WITH VOLATILE MATTER

Fig. 1

with some difficulty that we were able to obtain one sample of coal containing over 95 per cent. carbon. The porosity figure for this is of the same order as that of a coal of less than 82 per cent. carbon. There is no satisfactory explanation for the wide scattering of the values for lower-rank coals of less than about 83 per cent. carbon.

After this original work was done it was established that the shape of the porosity curve is an indication of the suitability of various coals for cleaning by froth flotation and of the relative amounts of oil required to render different coals free from dust during handling.

VARIATION OF COAL POROSITY WITH RANK.

Fig. 2

Experiments on the heat of wetting of 10 to 20 mesh coal carried out at the Fuel Research Station during 1924 gave an indication that the heat of wetting curve would resemble these porosity curves. Only a few samples of coal were examined and these gave the following results with water.

Coal	Carbon per cent.	Hydrogen per cent.	Volatile matter per cent.	Air-dried moisture per cent.	Heat of wetting cal. per gram.
1	86·3	5·3	34·0	1·3	1·2
2	84·8	5·3	35·9	4·0	2·9
3	77·4	5·1	41·4	11·7	9·2
4	67·0	5·4	68·0	18·8	17·4

By the same technique a beech charcoal (moisture 9·6%) gave a value of 6·7 cals. per gm. and two low-temperature cokes 3·4 and 1·8 cals. respectively. The low-temperature coke which gave the higher value was one prepared from a weakly-caking coal and the porous structure of the original coal was preserved in the coke. In the other coke the structure of the coal had been replaced by the bubble structure caused by the escape of gases from the fused coal.

It is interesting to observe that the four coal points would fall within or near the band occupied by the group of points in the heat of wetting curve published by Bangham and others in Information Circular I.C.U.R.A. 31. Since it is to be expected that high porosity would be associated with a high specific surface, the correlation between the heat of wetting and porosity is not surprising.

The correlation between porosity and heat of wetting makes it possible to obtain an indication of the average diameter of the capillaries in coal. It would appear that each 1% of porosity contributes about 1 cal. per gram of the heat of wetting. From Bangham's work this is equivalent to 10 sq. metres of surface per gm. of coal, so that, from the volume and the surface areas of the capillaries it is possible to calculate their mean diameter to be about 40Å.

Moisture Sorption

Further data on pore size have been obtained from vapour pressure measurements on the lines of the work of Porter and Ralston (8), but carried out with a more accurate control of temperature and with a positive circulation of nitrogen of controlled humidity through the bed of coal. The equilibrium moisture content of the coal corresponding to each stage of humidity was determined with progressively decreasing humidity and also with increasing humidity. In order to make sure that equilibrium was reached a period of 80/100 hours was necessary for each step. The length of this period was due to the slow rate at which the smaller pores became effective. A characteristic series of curves for a weakly caking Yorkshire coal (d.a.f. carbon 82%) is shown in Figure 3. The characteristic hysteresis loop shows clearly that, within a certain range of humidity, the ability of the coal to hold moisture depends upon whether the conditions of measurement are reached by sorption or desorption. The curves incidentally illustrate the important fact that when the "air-dry" moisture of coal is quoted it should relate not only to a constant relative humidity but also to the direction in which equilibrium is approached. Although in the past "air-dry" moisture in a coal has been held to be characteristic of that coal, it has been true only in those cases where special precautions have been taken.

Changes which are not reversible may take place in bituminous coal during the initial drying of freshly mined coal. Whether this is due to shrinkage is not clear but it does appear to be due to alterations in internal structure. The point A in Figure 3 indicates the moisture content of this coal in the mine and the curves indicate that the sorptive capacity expressed by the curve AO was never regained.

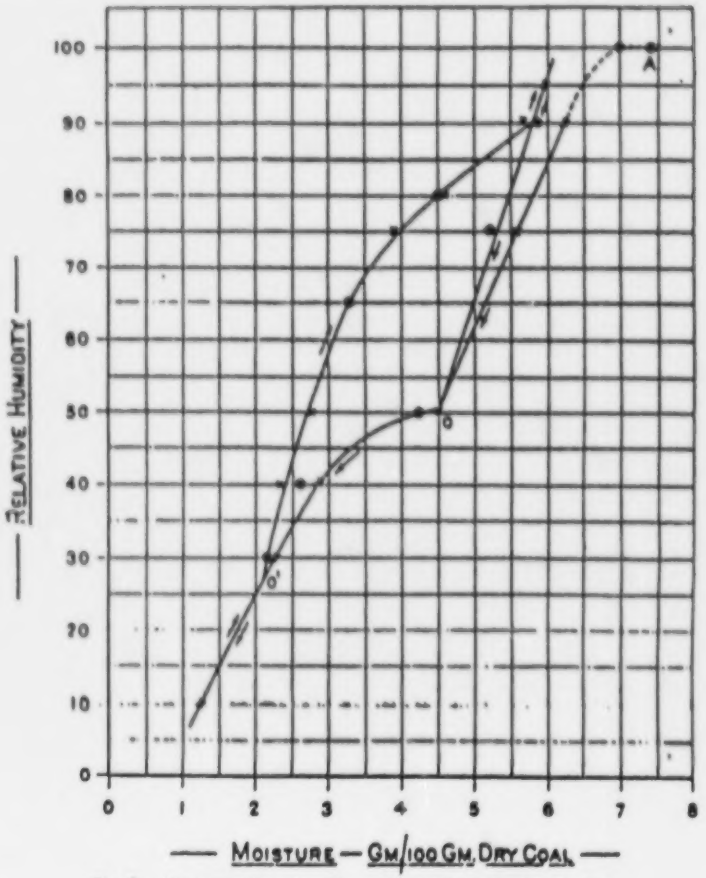


Fig. 3. Moisture Sorption Curves for a Coal of 82% Carbon.

The vapour-pressure diagram for silica gel obtained by van Bemmelen (10) is of a similar type to that of bright coal. It has been interpreted by Zsigmondy (11) who has calculated the pore diameter on that part of the curve where hsyteresis occurs and where the condition of the water in the capillaries is known. McBain (12) considers this method of calculation sound but holds that pore diameter cannot be calculated on the assumption that all the

sorbed water is held by capillary condensation; this throws doubt also on the pore size analysis figures deduced by Rosin, Rammeler and Kayser (13) and others. We have found that the behaviour of British coals rich in vitrain conforms more closely to the silica gel diagram than do the coals examined by Porter and Ralston (8) and we have therefore used Zsigmondy's method for the calculation of predominant pore size. One explanation of the hysteresis effect in sorption is that the lowering of the vapour pressure is due to the curvature of the meniscus of the water condensed in the capillaries, and

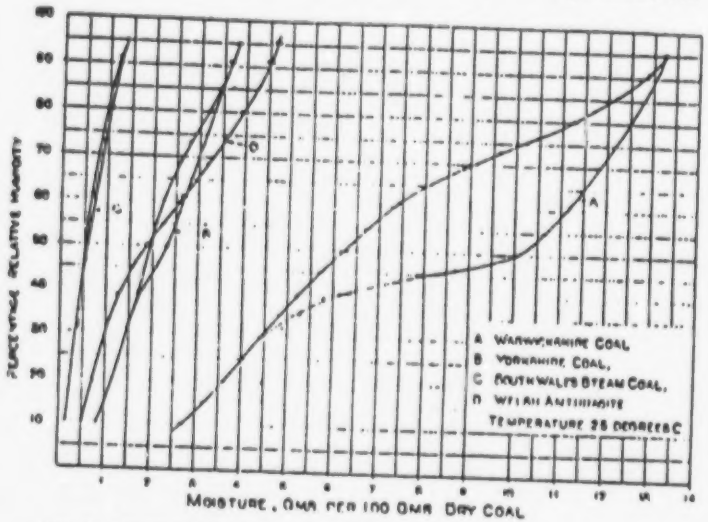

A WARWICKSHIRE COAL
B YORKSHIRE COAL,
C SOUTH WALES STEAM COAL,
D WELSH ANTHRACITE
TEMPERATURE 25 DEGREES C
MOISTURE, GMS PER 100 GMS DRY COAL

FIG. 4. MOISTURE SORPTION BY COALS OF DIFFERENT RANK.

that this curvature depends upon whether the meniscus is advancing or receding. The approximately horizontal part of the hysteresis curve corresponds to the stage at which the capillaries are emptying and Zsigmondy's method was to calculate the capillary diameter of the silica gel from the known lowering of vapour pressure at this stage. The calculation in the case of the British coals examined indicates the presence of a considerable number of capillaries with diameters between 20 and 40Å which confirms the value obtained above and suggests that it is not far from the truth.

It is also interesting to observe that the hysteresis loop varies considerably with the type of coal; Figure 4 illustrates the behaviour of four coals of quite different rank. Although the moisture contents at 95% humidity are in the order of the porosities of these coals, the width of the loop is seen to increase markedly on decrease of rank, being practically zero for anthracite. If we accept the above

interpretation of the hysteresis loop then the widths of the loops indicate the total volumes of the appropriate capillaries in the four coals. Taking these volumes to be 0·0, 0·4, 0·1 and 0 for the four coals and assuming a mean capillary diameter of 30Å, their average spacing may be calculated to be about 150, 500, 1,000 and over 1,000Å respectively.

These values for micellar size agree approximately with those deduced from the heat of wetting experiments but are 20 to 30 times greater than those deduced by Mahadevan (14) using an X-ray diffraction method. The increase in micellar size with rank does, however, agree with Riley's theory (15) of slow molecular condensation in the process of formation of coal.

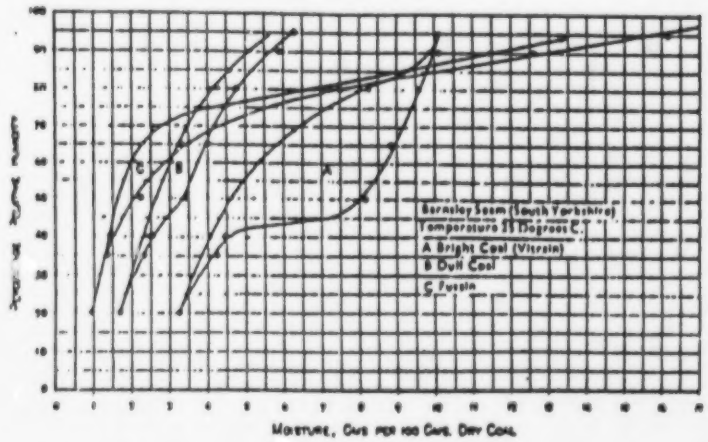

Barnsley Seam (South Yorkshire)
Temperature 25 Degrees C.
A Bright Coal (Vitrain)
B Dull Coal
C Fusain
MOISTURE, GMS PER 100 GMS. DRY COAL

FIG 5. MOISTURE SORPTION BY THE PURIFIED CONSTITUENTS OF COAL.

The internal structure of coal cannot be studied fully without taking into consideration the petrological components. We have already said that the behaviour of bright coals (vitrain) towards moisture is similar to that of a material like silica gel. It is of interest now to consider whether the other components behave differently. If we take vitrain, durain and fusain from the Barnsley seam we find the variations illustrated in Figure 5. The vitrain hysteresis loop is very similar to that of Figure 3 but the durain and fusain loops are much narrower suggesting that these components contain a smaller proportion of capillaries of small size. Since the overall porosities of durain and fusain are not less than that of vitrain it follows, therefore, that their average capillary diameters are larger. This conclusion is supported by a study of the penetration of various types of coal by oil (1) and also by inorganic salt solutions, as observed by radiographic examination.

Penetration of Salt Solutions into Coal.

When coal is examined by radiographic methods the positions of cracks and partings can be seen quite clearly. These cracks can be shown up more clearly by soaking the coal specimen in a solution of a lead salt before photographing. Local concentrations of lead salt then emphasise the position of partings, fusain bands, etc. and cracks which may be large and rare, or small and frequent, in different coals. It is possible that this cracking is affected by the method of mining and that further study might lead to an alteration in mining methods which would render certain coals less liable to breakage than at present.

An extension of this method to the study of micro-structure was developed at the Fuel Research Station by Beeching (16). The technique used was to study by X-ray shadow photographs the progress of lead salt solutions upwards into sections of coal immersed in the solution. From the rate of advance and the physical constants of the solution, the equivalent pore diameter could be calculated. When the advance was taking place along the bedding plane of durain the calculations indicated the existence of capillaries of about 500Å diameter. The rate of advance in the smaller capillaries could not be determined since they were obscured in the photograph. When the rate of advance was measured across the bedding plane it was very much slower indicating that the porosity of durain is very greatly influenced by its banded structure.

Vitrain behaves quite differently from durain; even after several days immersion there is little appreciable penetration. This has been confirmed by Land (17). Whether the cause is the relative absence of banded structure only, or the filling of the fine pores with water and a strong resistance to viscous flow, the results confirm the conclusions reached by other methods that the capillaries of vitrain are very much finer than those of durain although the possibility still remains that the existence of some fine pores in durain was obscured by the rapid advance of the solution in the larger pores. This method of investigating the porosity of coal would certainly repay further study; by the use of less opaque solutions it might be possible to measure the rate of movement of the liquid in the smaller pores by measuring the rate of increase of opacity behind that caused by the advance in the larger pores.

The Caking Power of Coal.

In the utilisation of coal for many industrial processes caking power is a most important factor. When considering caking power in relation to porosity, however, it must be borne in mind that the initial porosity of the coal may disappear before the coal takes part in the reactions of the process. This is true, for example, in the manufacture of coke from caking coals where a secondary structure is formed by the almost complete fusion of the coal, the secondary

structure being a bubble structure formed by the escape of gas and being of a different character from that of the original coal.

This change also takes place when a caking coal burns since fusion is necessarily a stage in the heating up of the coal. Only in those cases therefore, where the original structure of the coal can be preserved or modified without the formation of bubble structure, is original porosity of importance. For example, in Fuel Research experiments upon the manufacture of respirator carbon (18) from

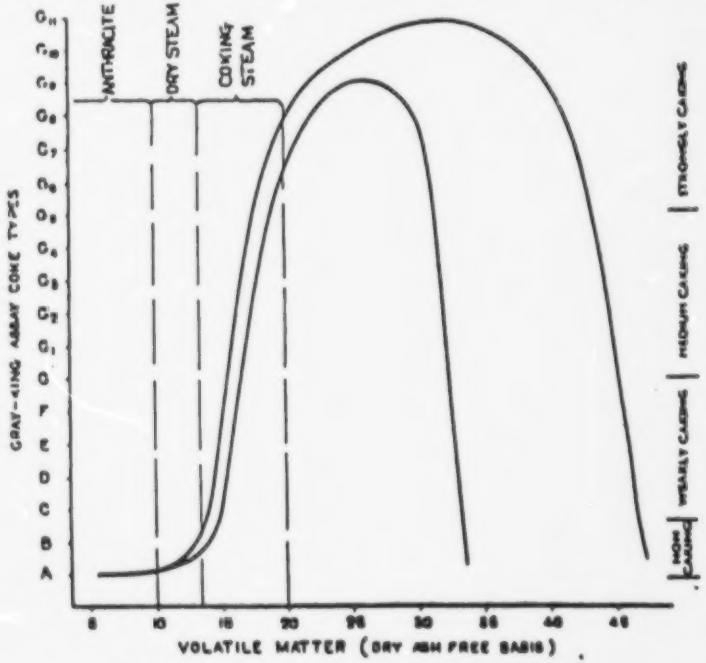


Fig. 6. Variation of Caking Power with Volatile Matter.

coal it was found that the important factors were (*a*) an inherent high porosity in the coal and (*b*) a degree of caking power which was just sufficient to cause incipient fusion and hardening to form a hard coke which still retained much of the original coal structure. When this porous structure was further developed by steam it gave the resulting carbon a high adsorptive power. It was found in this work that it was possible by a close definition of the properties of porosity and caking power to select coals suitable for the purpose.

The scale of caking power which has been favoured in the Coal Survey is the definition of the type of coke obtained in the Gray-King assay. Figure 6 illustrates the variation of caking power on this

scale in relation to volatile matter. It is interesting to observe that this curve is really an inversion of the porosity/volatile matter curve of Figure 1. It shows the same characteristic maximum (or minimum) and the same wide spread in the results at about 35% volatile matter. The curve yields further confirmation of the fact that the physical properties of coal are all interconnected.

A system of classification of industrial coals based upon Figure 6 is now in use by the Ministry of Fuel and Power to assist in the allocation of coals of different types to the industrial uses for which they are best suited. Each group of coals covers a part of the area of the band.

Conclusions.

The main conclusion which must be drawn at present is that not nearly enough is known about the internal structure of coal and that further study must be encouraged.

Secondly, it is interesting to record the fact that the variation of many of the physical properties of coal with rank follows a parabolic curve or band which is not peculiar to any one property. The properties related to rank in this way are porosity, heat of wetting, calorific value (9) sorption of oil in flotation and dustproofing (20), moisture content at standard humidity, sorption of dyes (21) friability (19), and caking power. Of these, the last requires some comment; there is no obvious reason why a property like caking power, which has always been associated with the proportion of certain constituents, should be related to physical properties like porosity or heat of wetting.

The above work was carried out as part of the programme of the Fuel Research Board and is published by permission of the Department of Scientific and Industrial Research.

REFERENCES.

1. King, *Chem. and Ind.*, 1939, 58, 94.
2. *Report of Fuel Research Board*, 1937-8, p. 98.
3. Harkins and Ewing, *J. Amer. Chem. Soc.*, 1921, 43, 1787.
4. Coldman and Polanyi, *Z. physikal. Chem.*, 1928, 132, 321.
5. Howarth and Hewlett, *J. Phys. Chem.*, 1924, 28, 1082.
6. Lea, *Fuel*, 1928, 7, 430.
7. King, Maries and Crossley, *J. Soc. Chem. Ind.*, 1930, 58, 277T.
8. Porter and Ralston, *U.S. Bureau of Mines Tech. Paper*, 113 (1916).
9. *Fuel Research Survey Paper No. 55* (1942)
10. van Bemmelen, "*Die Absorption*" (1910).
11. Zsigmondy, *Z. anorg. Chem.*, 1911, 71, 356.
12. McBain, "*Sorption of Gases and Vapours by Solids*" (1932).
13. Rosin, Rammler and Kayser, *Braunkohle*, 1934, 33, 289.
14. Mahadevan, *Fuel*, 1930, 9, 574.
15. Riley, *Gas World (Coking Sect.)*, 1937, 107, 110.
16. Hirschmann, *J. Inst. Fuel*, 1938, 12, 38.
17. Land, *Ind. Eng. Chem.*, 1942, 34, 1078.
18. *Fuel Research Tech. Paper*, 47, 1938.
19. Yancey and Johnson, *Trans. Amer. Inst. Min. Met. Eng.*, 1932, 101, 171.
20. *Report of Fuel Research Board*, 1937-8, pp. 91, 97.
21. Swietoslawski, "*Coke formation process and physico chemical properties of coals*" (*Polish Inst. Arts and Sciences in America*), 1942.

THE INHERENT MOISTURE IN COAL

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Introduction.

In addition to free or surface moisture which may be detected by touch or sight, coal, even if superficially dry, may contain inherent moisture which, *under normal atmospheric conditions*, can only be completely expelled by drying at 100°C. It is now generally held that this inherent moisture is adsorbed or condensed on the internal capillary surfaces within the coal itself, and that the amount which a coal can hold is dependent upon the extent of these internal surfaces. It is well known that there is a relationship between the rank of a coal and its inherent moisture content, and it is most probable that the inherent moisture, if accurately determined, is a measure not only of the capillary surface area of the coal but also of its rank and of the properties and behaviour associated with it, such as coking and swelling properties, reactivity, and adsorptive capacity for oil in dust proofing.

The amount of inherent moisture held by a coal is not an absolute quantity unless the conditions under which it has been determined are precisely defined, because the moisture in the coal always tends towards equilibrium with the vapour pressure in the atmosphere to which it is exposed.

The inherent moisture is at a maximum when it is in equilibrium with saturated air, *i.e.* air of 100 per cent. humidity. When the coal is exposed to air of a lower humidity it loses water until equilibrium is again reached between the vapour pressures of the moisture in the coal and in the air. The whole of the moisture can be lost in an absolutely dry atmosphere maintained by exposure over P_2O_5 or anhydrous sulphuric acid. It is, therefore, impossible to define inherent moisture apart from the atmosphere with which it is in equilibrium, and the air dried moistures of different coal samples as usually given, are not strictly comparable because they have been determined on coals air dried under conditions of exposure which are not necessarily the same. Consistent and comparable results can only be obtained on coals air dried in an atmosphere of controlled humidity and temperature.

It is not easy to determine the maximum or true inherent moisture of a coal because it is first necessary to obtain equilibrium at 100 per cent. humidity, under which conditions free or surface

APPENDIX A-2

Stansfield, E., Lang, W.A., Sutherland, J.W., Gilbert, K.C. and Zeavin, S., 1927: Specific gravity of coal; Scientific and Industrial Research Council of Alberta, Report No. 22, p. 21 - 23.

Stansfield E., Lang, W.A., Gilkart, K.C. and Evans, S., 1922: Scientific and Industrial Research Council of Alberta, Rept. No. 22.

minations were also made on the same coals, after these had been exposed to a current of air at 105°C for six hours: but these results have been omitted from the table. The oxidisability of a coal, as measured by this test, increases with oxidation in hot air. In the same way a weathered coal gives a higher value than a fresh coal from the same mine. It will thus be seen that as a coal matures from lignitic to anthracitic character its oxidisability decreases, but if coal of any character becomes weathered its oxidisability increases, and its apparent maturity decreases.

SPECIFIC GRAVITY OF COAL.

Determinations have been made of the specific gravity of a number of coal samples. The samples were separated by hand into portions of differing cleanliness, where this was possible, and the specific gravity and analysis of each portion determined. In some cases samples of bone coal were also tested in order to get a wide range of ash content.

Two specific gravities are reported, "apparent" and "real". A lump of coal normally contains many microscopic cells filled with air or gas. The apparent specific gravity is the specific gravity of the lump as it occurs. The real specific gravity is that of the coal substance. The apparent specific gravity is the value to be employed for calculating the weight of a cubic foot of coal as mined and for similar practical applications, but as the real specific gravity can be determined with the greater accuracy, both values are given. The relation between the two values is an indication of the porosity of the coal, the greater the difference between the two values the greater the porosity.

The mineral impurities in a coal are denser than the coal substance, so that, with a few exceptions noted below, the density of any coal increases with the ash. In the table of values reported a number of minor discrepancies will be noticed where a slight increase in ash is accompanied by a decrease in specific gravity. This may be due to a variation either in the coal or in the mineral impurity. It has been noted that with certain coals there is a minimum specific gravity with approximately 3 or 4 per cent. of ash. From this point the density increases with either an increase or a decrease of the ash. It is probable that these extremely low ash samples of coal are largely vitrain and contain little or no fusian or animal charcoal.

The specific gravity changes not only with the ash content of the sample but also with its moisture content. When a lump of high moisture coal dries out the lump shrinks and checks, but it also becomes more porous, so that the apparent specific gravity decreases. No data has yet been collected to correlate the apparent specific gravity of a sample with its moisture content. On the other hand, as the moisture which escapes has a specific gravity of unity and the dry coal substance has a specific gravity of about 1.3 the more the sample dries out the higher its real specific gravity becomes. It has not yet been possible to determine the change of real specific gravity over a wide range of moisture content, but within

narrow limits it can be assumed that a decrease of 1% in the moisture content will increase the real specific gravity 0.004 with samples of 1.3 specific gravity, and 0.006 with samples of 1.4 specific gravity.

The results reported in Table III show the moisture and ash content of each portion tested, as well as the determined specific gravities. Slight adjustments have been made in the reported real specific gravities to adjust these values to the same moisture content as for the reported apparent specific gravities. It is hoped eventually to prepare curves showing the relations between the moisture and ash and the specific gravities of different samples of a series of typical coals of the province, but too few determinations have so far been made.

A number of determinations were made of samples taken in 1927, but as the technique of the determination was subsequently improved, the only values reported in the table are those of samples taken early in 1928.

TABLE III.—SPECIFIC GRAVITIES OF COAL AND BONE COAL.

Sample No. Mine and Area	Moisture %	Ash %	Specific Gravity	
			Apparent	Real
(a) Bituminous Coals.				
14-28	1.2	4.6	1.289	1.319
Mountain Park	1.1	4.9	1.279	1.325
Mountain Park Area	0.6	6.4	1.289	1.342
13-28	0.9	7.4	1.329	1.360
Blue Diamond	1.0	7.7	1.326	1.351
Brule Area	0.8	11.2	1.385	1.415
17-28	1.1	3.0	1.306	1.333
Dennison	1.2	10.9	1.378	1.397
Crowsnest Area	0.8	29.6	1.583	1.625
305-28	5.8	1.9	1.328	1.371
Christine	5.2	2.8	1.344	1.386
Crowsnest Area	6.6	5.9	1.365	1.401
(b) Sub-bituminous Coals.				
304-28	7.2	5.1	1.335	1.387
Saunders Ridge	7.3	6.9	1.363	1.389
Coalspur Area	6.9	9.2	1.393	1.424
313-28	9.1	3.3	1.334	1.357
Alexo Mine	7.1	5.0	1.317	1.350
Saunders Area	7.4	12.1	1.385	1.424
314-28	5.5	4.1	.....	1.326
Du Rocher	6.0	5.0	1.312	1.343
Pekisko Area	6.3	11.5	1.409	1.439
18-28 & 316-28	4.3	7.5	1.319	1.333
Rhodes Mine	4.1	9.3	1.332	1.358
Pincher Area	4.2	13.9	1.359	1.380
	4.7	17.2	1.384	1.414
	5.1	21.0	1.424	1.453
312-28	5.8	7.2	1.351	1.384
Beazer	5.6	8.1	1.357	1.395
Magrath Area	5.2	11.4	1.381	1.422
301-28	10.3	5.1	1.321	1.355
Lethbridge	9.2	5.8	1.324	1.338
Lethbridge Area	10.5	10.6	1.366	1.381
21-28	10.2	6.0	1.329	1.346
Galt	11.9	10.9	1.378	1.400
Lethbridge Area	12.5	11.6	1.360	1.380
	10.0	12.8	1.388	1.406

(c) Domestic Coals.

Sample No. Mine and Area	Moisture %	Ash %	Specific Gravity	
			Apparent	Real
308-28	15.0	6.2	1.338	1.366
Bridge End	14.7	7.0	1.354	1.378
Taber Area	14.2	7.4	1.356	1.383
309-28	24.8	3.6	1.309	1.327
Anon	20.3	5.9	1.331	1.358
Taber Area	19.6	8.3	1.345	1.394
311-28	14.1	3.8	1.325	1.348
Aborn	12.7	7.0	1.342	1.364
Milk River Area	12.2	16.1	1.430	1.461
310-28	20.9	4.1	1.312	1.324
Hughson	19.1	7.4	1.347	1.381
Milk River Area	17.8	10.6	1.393	1.411
307-28	17.6	3.8	1.322	1.361
Pembina	18.3	5.2	1.340	1.370
Pembina Area	17.7	7.1	1.351	1.392
324-28	24.9	4.3	1.311	1.325
Cardiff	27.4	4.8	1.298	1.317
Edmonton Area	25.2	5.0	1.315	1.328
	21.1	15.0	1.385	1.397
319-28	24.2	3.9	1.286	1.331
Black Diamond	22.6	8.0	1.337	1.360
Edmonton Area	21.5	8.8	1.332	1.362
318-28	26.4	3.1	1.281	1.320
Dobell	25.2	3.8	1.274	1.325
Tofield Area	24.8	7.4	1.318	1.343
317-28	24.1	4.4	1.300	1.332
Stoney Creek	23.8	5.2	1.316	1.343
Camrose Area	.....	.....	.....	.....
320-28	27.0	7.2	1.332	1.349
O.K.	24.1	12.6	1.360	1.378
Castor Area	25.5	16.3	1.402	1.415
306-28	25.0	4.8	1.305	1.332
New Walker	26.3	5.3	1.309	1.335
Sheerness Area	25.4	9.9	1.339	1.362
323-28	18.8	4.3	1.329	1.369
Carbondale	18.0	7.8	1.336	1.396
Ardley Area	17.2	9.0	1.352	.....
	19.6	8.8	.....	1.403
322-28	19.9	3.4	1.328	1.354
Big Valley	21.9	5.6	1.331	1.355
Big Valley Area	.....	.....	.....	.....
321-28	14.1	7.4	1.348	1.380
Carbon Black	15.7	7.8	1.351	1.375
Carbon Area	14.4	8.0	1.352	1.376
302-28	19.5	2.3	1.320	1.340
Elgin	19.6	3.8	1.314	1.336
Drumheller Area	19.4	4.0	1.315	1.336
19-28	17.4	3.5	1.308	1.331
Hy Grade	17.0	3.7	1.309	1.333
Drumheller Area	16.4	15.4	1.398	1.417
	16.0	22.7	1.454	1.472
303-28	18.9	3.2	1.319	1.342
Midland	18.3	7.0	1.333	1.353
Drumheller	18.3	7.6	1.335	1.354
16-28	12.2	5.3	1.336	1.363
Popovich and Vanbesien	12.5	5.7	1.342	1.368
Champion Area	12.8	6.0	1.347	1.368
315-28	13.4	6.9	1.356	1.376
Ellis	.....	.....	.....	.....
Champion Area	.....	.....	.....	.....

APPENDIX A

SELECTED PUBLICATIONS

APPENDIX A-1

King, J. G. and Wilkins, E.T., 1944: The internal structure of coal; Proceedings, Conference on Ulta-Fine Structure of Coals and Cokes; British Coal Utilization Research Authority, p. 46-56.

THE INTERNAL STRUCTURE OF COAL

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(Received 12th May, 1943)

DURING 1938 one of us pointed out at a meeting of the Society of Chemical Industry in Newcastle (1) the importance of studying the internal structure of coal in order to obtain a greater insight into its behaviour in industrial processes.

Although our knowledge of the properties of coal has reached the stage where we can recognise readily the gradual change of properties with carbon content, the study of the internal structure of coal has not been pursued actively enough despite the fact that it has been recognised for many years that coal has a micro-porous structure which is different in different types of coal.

During a number of years prior to the War the study of the physical structure of coals had become of special interest at the Fuel Research Station, not so much as a separate programme, but in connection with other researches such as those upon the cleaning of coal by froth flotation processes, the manufacture of active carbon, and the preparation of reactive fuels for the gas producer. Although war-time programmes have delayed progress since 1939, it is of interest to review for the purposes of this Conference the work which has been done, recognising that it is too early yet to draw conclusions except in certain details. Some of the work has already been reported in the Annual Reports of the Fuel Research Board.

The technique used has involved determinations of the heat of wetting, studies of ultimate porosity as measured in several different ways, and other aspects of coal structure.

The Porosity of Coal.

Much of our attention has been concentrated upon the examination of the free space within the coal substance. Our observations support the view that in general coal is interspersed by pores or capillaries of various sizes which give it a sponge-like structure. The diameter and extent of these capillaries is a measure of total internal surface, but their nature largely determines the effect of that surface upon the properties of the coal. The smallest capillaries are capable of becoming filled with condensed vapours, a form of capillary condensation which will not be shown by the larger pores, the latter acquiring a surface film only. The size of the pores in coal therefore presumably determines the accessibility of the internal surfaces and

it may be that while the smallest pores will exert their influence in slow chemical reactions such as those which occur during weathering, the larger capillaries will play the more important part in rapid reactions, possibly including those of combustion. When it becomes possible, therefore, to present a complete picture or analysis of the pore structure of any coal, we shall have gone a long way towards understanding its properties and its behaviour in reactions of different types.

The method of determining the percentage of total free space within porous substances by calculation from their true and apparent specific gravities is well known, but the only application to coal appears to be that published in the Report of the Fuel Research Board (2). In applying this method to coal, porosity was calculated from the true specific gravity of the finely-ground coal and the apparent specific gravity of dust-free coal (over $\frac{1}{72}$ in.) by displacement in mercury.

A second simple method adopted was to impregnate the coal with water, allow it to dry until the surface film of moisture just disappeared and then to calculate the moisture content as a measure of the total volume of the capillaries.

In both cases the methods are applicable to coals of any ash content and although the technique is of the simplest, it is interesting to find that the results are repeatable to a satisfactory extent.

Porosity results obtained in these ways are, of course, not absolute values. In the case of charcoal the observed specific gravity depends partly upon the liquid used. Harkins and Ewing (3) have shown the possibility that this effect is due to the different compressibilities of liquids, and Goldman and Polanyi have concluded (4) that the actual value of the specific gravity is generally less than the observed value. Howard and Hewlett (5), however, after studying various liquids, have concluded that, with certain media, the incomplete penetration of very fine pores may yield low results. Lea (6) has observed a superficial expansion of coal on wetting, which may affect the value, but our results suggest that any error in the porosity figure obtained due to expansion is within the experimental limits of accuracy of the simple methods adopted.

We have calculated the porosity values of a large number of British coals of different rank and have shown these graphically in Figures 1 and 2, plotting the percentage porosity against the rank of the coal expressed in terms both of volatile matter and of carbon The results should more suitably have been expressed on the basis o pure coal calculated by the method of King, Maries and Crossley (7) but they are expressed in this case on the dry ash-free basis in orde: to include a larger number of coals for which the mineral matte: correction had not been obtained. Owing to the dispersion of the points within the porosity band so obtained it is unlikely that cal culation to pure coal would yield a different pattern. This has beer checked where possible and found to be so.

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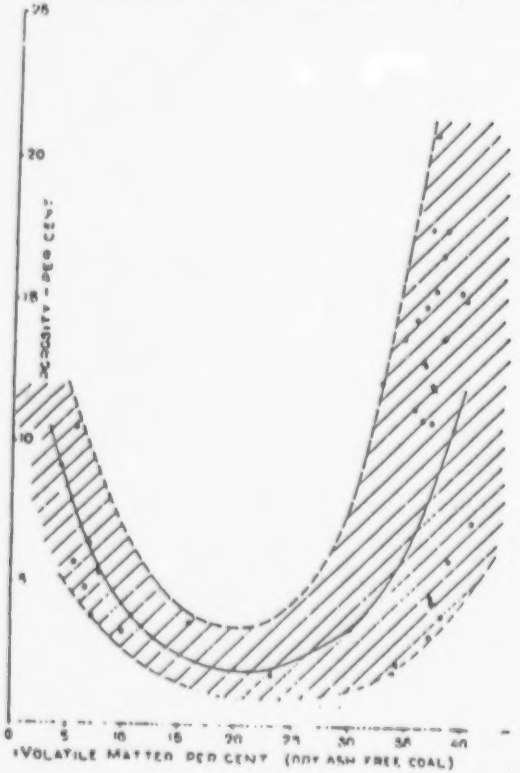
The general trend in these porosity curves is an indication of high porosity at low rank, minimum porosity in the neighbourhood of 89 per cent. carbon or 20 per cent. volatile matter, and a tendency for porosity to increase again in the anthracite range. It was only

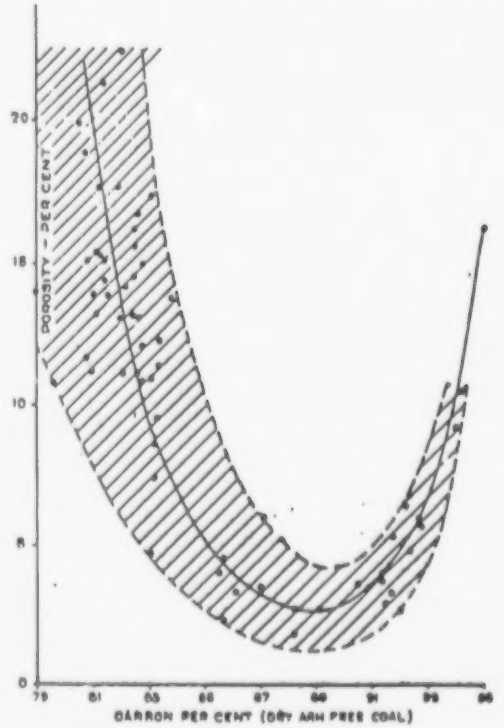


VARIATION OF COAL POROSITY WITH VOLATILE MATTER

Fig. 1

with some difficulty that we were able to obtain one sample of coal containing over 95 per cent. carbon. The porosity figure for this is of the same order as that of a coal of less than 82 per cent. carbon. There is no satisfactory explanation for the wide scattering of the values for lower-rank coals of less than about 83 per cent. carbon.

After this original work was done it was established that the shape of the porosity curve is an indication of the suitability of various coals for cleaning by froth flotation and of the relative amounts of oil required to render different coals free from dust during handling.



VARIATION OF COAL POROSITY WITH RANK.

Fig. 2

Experiments on the heat of wetting of 10 to 20 mesh coal carried out at the Fuel Research Station during 1924 gave an indication that the heat of wetting curve would resemble these porosity curves. Only a few samples of coal were examined and these gave the following results with water.

Coal	Carbon per cent.	Hydrogen per cent.	Volatile matter per cent.	Air-dried moisture per cent.	Heat of wetting cal. per gram.
1	86·3	5·3	34·0	1·3	1·2
2	84·8	5·3	35·9	4·0	2·9
3	77·4	5·1	41·4	11·7	9·2
4	67·0	5·4	68·0	18·8	17·4

By the same technique a beech charcoal (moisture 9·6%) gave a value of 6·7 cals. per gm. and two low-temperature cokes 3·4 and 1·8 cals. respectively. The low-temperature coke which gave the higher value was one prepared from a weakly-caking coal and the porous structure of the original coal was preserved in the coke. In the other coke the structure of the coal had been replaced by the bubble structure caused by the escape of gases from the fused coal.

It is interesting to observe that the four coal points would fall within or near the band occupied by the group of points in the heat of wetting curve published by Bangham and others in Information Circular B.C.U.R.A. 31. Since it is to be expected that high porosity would be associated with a high specific surface, the correlation between the heat of wetting and porosity is not surprising.

The correlation between porosity and heat of wetting makes it possible to obtain an indication of the average diameter of the capillaries in coal. It would appear that each 1% of porosity contributes about 1 cal. per gram of the heat of wetting. From Bangham's work this is equivalent to 10 sq. metres of surface per gm. of coal, so that, from the volume and the surface areas of the capillaries it is possible to calculate their mean diameter to be about 40Å.

Moisture Sorption

Further data on pore size have been obtained from vapour pressure measurements on the lines of the work of Porter and Ralston (8), but carried out with a more accurate control of temperature and with a positive circulation of nitrogen of controlled humidity through the bed of coal. The equilibrium moisture content of the coal corresponding to each stage of humidity was determined with progressively decreasing humidity and also with increasing humidity. In order to make sure that equilibrium was reached a period of 80/100 hours was necessary for each step. The length of this period was due to the slow rate at which the smaller pores became effective. A characteristic series of curves for a weakly caking Yorkshire coal (d.a.f. carbon 82%) is shown in Figure 3. The characteristic hysteresis loop shows clearly that, within a certain range of humidity, the ability of the coal to hold moisture depends upon whether the conditions of measurement are reached by sorption or desorption. The curves incidentally illustrate the important fact that when the "air-dry" moisture of coal is quoted it should relate not only to a constant relative humidity but also to the direction in which equilibrium is approached. Although in the past "air-dry" moisture in a coal has been held to be characteristic of that coal, it has been true only in those cases where special precautions have been taken.

Changes which are not reversible may take place in bituminous coal during the initial drying of freshly mined coal. Whether this is due to shrinkage is not clear but it does appear to be due to alterations in internal structure. The point A in Figure 3 indicates the moisture content of this coal in the mine and the curves indicate that the sorptive capacity expressed by the curve AO was never regained.

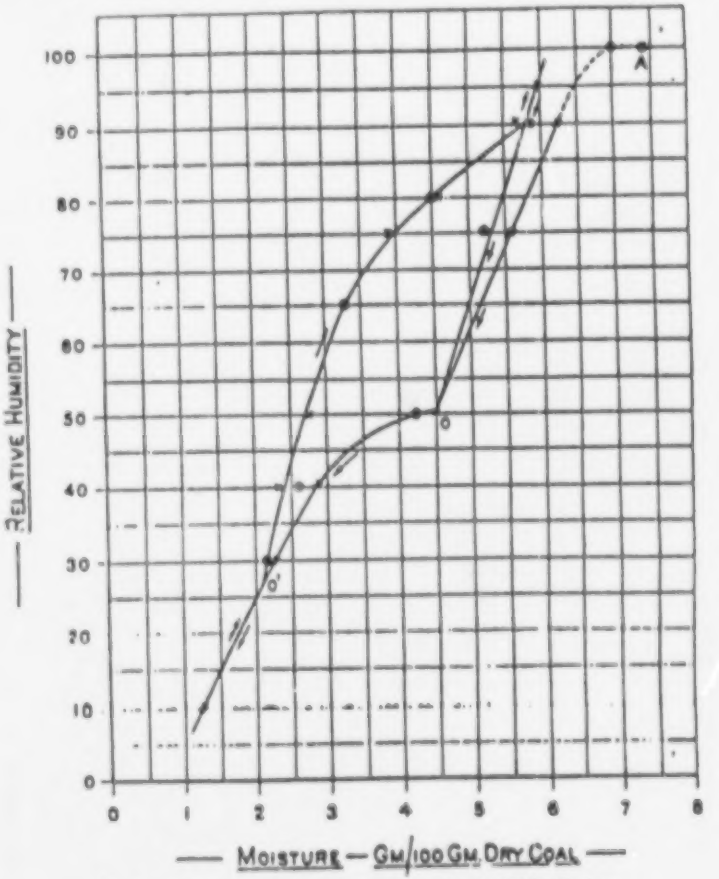


Fig. 3. Moisture Sorption Curves for a Coal of 82% Carbon.

The vapour-pressure diagram for silica gel obtained by van Bemmelen (10) is of a similar type to that of bright coal. It has been interpreted by Zsigmondy (11) who has calculated the pore diameter on that part of the curve where hysteresis occurs and where the condition of the water in the capillaries is known. McBain (12) considers this method of calculation sound but holds that pore diameter cannot be calculated on the assumption that all the

sorbed water is held by capillary condensation ; this throws doubt also on the pore size analysis figures deduced by Rosin, Rammeler and Kayser (13) and others. We have found that the behaviour of British coals rich in vitrain conforms more closely to the silica gel diagram than do the coals examined by Porter and Ralston (8) and we have therefore used Zsigmondy's method for the calculation of predominant pore size. One explanation of the hysteresis effect in sorption is that the lowering of the vapour pressure is due to the curvature of the meniscus of the water condensed in the capillaries, and

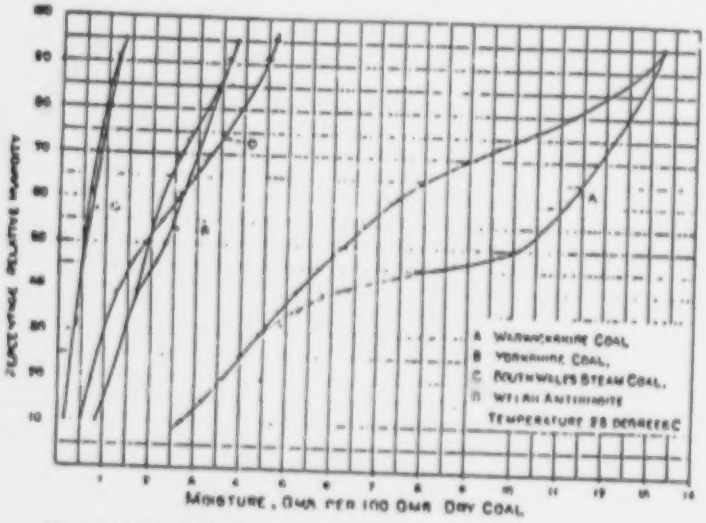

A Warwickshire Coal
B Yorkshire Coal,
C Southwales Steam Coal,
D Welsh Anthracite
Temperature 25 degrees C
Moisture, Gms per 100 Gms Dry Coal

Fig. 4. Moisture Sorption by Coals of Different Rank.

that this curvature depends upon whether the meniscus is advancing or receding. The approximately horizontal part of the hysteresis curve corresponds to the stage at which the capillaries are emptying and Zsigmondy's method was to calculate the capillary diameter of the silica gel from the known lowering of vapour pressure at this stage. The calculation in the case of the British coals examined indicates the presence of a considerable number of capillaries with diameters between 20 and 40Å which confirms the value obtained above and suggests that it is not far from the truth.

It is also interesting to observe that the hysteresis loop varies considerably with the type of coal ; Figure 4 illustrates the behaviour of four coals of quite different rank. Although the moisture contents at 95% humidity are in the order of the porosities of these coals, the width of the loop is seen to increase markedly on decrease of rank, being practically zero for anthracite. If we accept the above

interpretation of the hysteresis loop then the widths of the loops indicate the total volumes of the appropriate capillaries in the four coals. Taking these volumes to be 5·0, 0·4, 0·1 and 0 for the four coals and assuming a mean capillary diameter of 30Å, their average spacing may be calculated to be about 150, 500, 1,000 and over 1,000Å respectively.

These values for micellar size agree approximately with those deduced from the heat of wetting experiments but are 20 to 30 times greater than those deduced by Mahadevan (14) using an X-ray diffraction method. The increase in micellar size with rank does, however, agree with Riley's theory (15) of slow molecular condensation in the process of formation of coal.

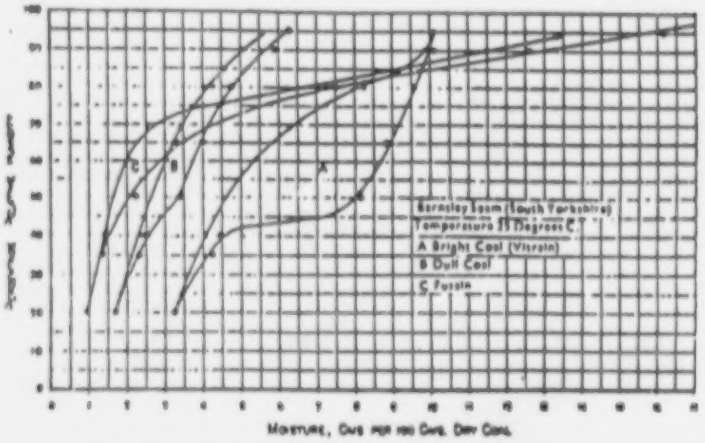

Barnsley Seam (South Yorkshire)
Temperature 25 Degrees C.
A Bright Coal (Vitrain)
B Dull Coal
C Fusain
Moisture, Gms per 100 Gms. Dry Coal

Fig 5 Moisture Sorption by the Banded Constituents of Coal.

The internal structure of coal cannot be studied fully without taking into consideration the petrological components. We have already said that the behaviour of bright coals (vitrain) towards moisture is similar to that of a material like silica gel. It is of interest now to consider whether the other components behave differently. If we take vitrain, durain and fusain from the Barnsley seam we find the variations illustrated in Figure 5. The vitrain hysteresis loop is very similar to that of Figure 3 but the durain and fusain loops are much narrower suggesting that these components contain a smaller proportion of capillaries of small size. Since the overall porosities of durain and fusain are not less than that of vitrain it follows, therefore, that their average capillary diameters are larger. This conclusion is supported by a study of the penetration of various types of coal by oil (1) and also by inorganic salt solutions, as observed by radiographic examination.

Penetration of Salt Solutions into Coal.

When coal is examined by radiographic methods the positions of cracks and partings can be seen quite clearly. These cracks can be shown up more clearly by soaking the coal specimen in a solution of a lead salt before photographing. Local concentrations of lead salt then emphasise the position of partings, fusain bands, etc. and cracks which may be large and rare, or small and frequent, in different coals. It is possible that this cracking is affected by the method of mining and that further study might lead to an alteration in mining methods which would render certain coals less liable to breakage than at present.

An extension of this method to the study of micro-structure was developed at the Fuel Research Station by Beeching (16). The technique used was to study by X-ray shadow photographs the progress of lead salt solutions upwards into sections of coal immersed in the solution. From the rate of advance and the physical constants of the solution, the equivalent pore diameter could be calculated. When the advance was taking place along the bedding plane of durain the calculations indicated the existence of capillaries of about 500Å diameter. The rate of advance in the smaller capillaries could not be determined since they were obscured in the photograph. When the rate of advance was measured across the bedding plane it was very much slower indicating that the porosity of durain is very greatly influenced by its banded structure.

Vitrain behaves quite differently from durain; even after several days immersion there is little appreciable penetration. This has been confirmed by Land (17). Whether the cause is the relative absence of banded structure only, or the filling of the fine pores with water and a strong resistance to viscous flow, the results confirm the conclusions reached by other methods that the capillaries of vitrain are very much finer than those of durain although the possibility still remains that the existence of some fine pores in durain was obscured by the rapid advance of the solution in the larger pores. This method of investigating the porosity of coal would certainly repay further study; by the use of less opaque solutions it might be possible to measure the rate of movement of the liquid in the smaller pores by measuring the rate of increase of opacity behind that caused by the advance in the larger pores.

The Caking Power of Coal.

In the utilisation of coal for many industrial processes caking power is a most important factor. When considering caking power in relation to porosity, however, it must be borne in mind that the initial porosity of the coal may disappear before the coal takes part in the reactions of the process. This is true, for example, in the manufacture of coke from caking coals where a secondary structure is formed by the almost complete fusion of the coal, the secondary

structure being a bubble structure formed by the escape of gas and being of a different character from that of the original coal.

This change also takes place when a caking coal burns since fusion is necessarily a stage in the heating up of the coal. Only in those cases therefore, where the original structure of the coal can be preserved or modified without the formation of bubble structure, is original porosity of importance. For example, in Fuel Research experiments upon the manufacture of respirator carbon (18) from

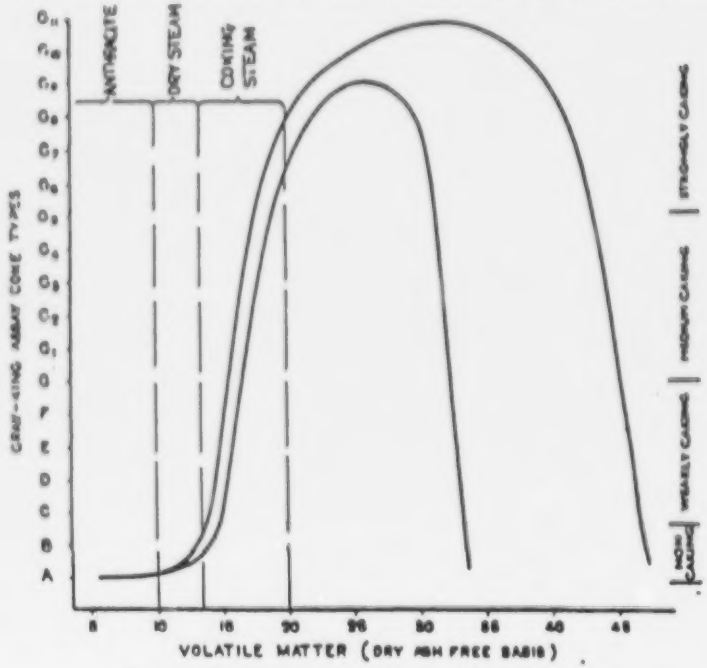


Fig. 6. Variation of Caking Power with Volatile Matter.

coal it was found that the important factors were (*a*) an inherent high porosity in the coal and (*b*) a degree of caking power which was just sufficient to cause incipient fusion and hardening to form a hard coke which still retained much of the original coal structure. When this porous structure was further developed by steam it gave the resulting carbon a high adsorptive power. It was found in this work that it was possible by a close definition of the properties of porosity and caking power to select coals suitable for the purpose.

The scale of caking power which has been favoured in the Coal Survey is the definition of the type of coke obtained in the Gray-King assay. Figure 6 illustrates the variation of caking power on this

scale in relation to volatile matter. It is interesting to observe that this curve is really an inversion of the porosity/volatile matter curve of Figure 1. It shows the same characteristic maximum (or minimum) and the same wide spread in the results at about 35% volatile matter. The curve yields further confirmation of the fact that the physical properties of coal are all interconnected.

A system of classification of industrial coals based upon Figure 6 is now in use by the Ministry of Fuel and Power to assist in the allocation of coals of different types to the industrial uses for which they are best suited. Each group of coals covers a part of the area of the band.

Conclusions.

The main conclusion which must be drawn at present is that not nearly enough is known about the internal structure of coal and that further study must be encouraged.

Secondly, it is interesting to record the fact that the variation of many of the physical properties of coal with rank follows a parabolic curve or band which is not peculiar to any one property. The properties related to rank in this way are porosity, heat of wetting, calorific value (9) sorption of oil in flotation and dustproofing (20), moisture content at standard humidity, sorption of dyes (21) friability (19), and caking power. Of these, the last requires some comment; there is no obvious reason why a property like caking power, which has always been associated with the proportion of certain constituents, should be related to physical properties like porosity or heat of wetting.

The above work was carried out as part of the programme of the Fuel Research Board and is published by permission of the Department of Scientific and Industrial Research.

REFERENCES.

1. King, *Chem. and Ind.*, 1938, 58, 94.
2. *Report of Fuel Research Board*, 1937-8, p. 99.
3. Harkins and Ewing, *J. Amer. Chem. Soc.*, 1921, 43, 1787.
4. Goldman and Polanyi, *Z. physikal. Chem.*, 1928, 132, 321.
5. Howard and Hewlett, *J. Phys. Chem.*, 1924, 28, 1082.
6. Lea, *Fuel*, 1928, 7, 430.
7. King, Mairs and Crossley, *J. Soc. Chem. Ind.*, 1930, 55, 277T.
8. Porter and Ralston, *U.S. Bureau of Mines Tech. Paper*, 113 (1916).
9. *Fuel Research Survey Paper No. 58* (1942).
10. van Bemmelen, "*Die Absorption*" (1910).
11. Zsigmondy, *Z. anorg. Chem.*, 1911, 71, 356.
12. McBain, "*Sorption of Gases and Vapours by Solids*" (1932).
13. Rosin, Rammler and Kavass, *Braunkohle*, 1934, 33, 289.
14. Mahadevan, *Fuel*, 1936, 9, 574.
15. Riley, *Gas World* (Coking Sect.), 1937, 107, 110.
16. Hirschmann, *J. Inst. Fuel*, 1938, 12, 35.
17. Land, *Ind. Eng. Chem.*, 1942, 34, 1078.
18. *Fuel Research Tech. Paper*, 47, 1938.
19. Yancey and Johnson, *Trans. Amer. Inst. Min. Met. Eng.*, 1932, 101, 171.
20. *Report of Fuel Research Board*, 1937-8, pp. 91, 97.
21. Swietoslawski, "*Coke formation process and physico chemical properties of coals*" (Polish Inst. Arts and Sciences in America), 1942.

THE INHERENT MOISTURE IN COAL

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Introduction.

In addition to free or surface moisture which may be detected by touch or sight, coal, even if superficially dry, may contain inherent moisture which, *under normal atmospheric conditions*, can only be completely expelled by drying at 100°C. It is now generally held that this inherent moisture is adsorbed or condensed on the internal capillary surfaces within the coal itself, and that the amount which a coal can hold is dependent upon the extent of these internal surfaces. It is well known that there is a relationship between the rank of a coal and its inherent moisture content, and it is most probable that the inherent moisture, if accurately determined, is a measure not only of the capillary surface area of the coal but also of its rank and of the properties and behaviour associated with it, such as coking and swelling properties, reactivity, and adsorptive capacity for oil in dust proofing.

The amount of inherent moisture held by a coal is not an absolute quantity unless the conditions under which it has been determined are precisely defined, because the moisture in the coal always tends towards equilibrium with the vapour pressure in the atmosphere to which it is exposed.

The inherent moisture is at a maximum when it is in equilibrium with saturated air, *i.e.* air of 100 per cent. humidity. When the coal is exposed to air of a lower humidity it loses water until equilibrium is again reached between the vapour pressures of the moisture in the coal and in the air. The whole of the moisture can be lost in an absolutely dry atmosphere maintained by exposure over P_2O_5 or anhydrous sulphuric acid. It is, therefore, impossible to define inherent moisture apart from the atmosphere with which it is in equilibrium, and the air dried moistures of different coal samples as usually given, are not strictly comparable because they have been determined on coals air dried under conditions of exposure which are not necessarily the same. Consistent and comparable results can only be obtained on coals air dried in an atmosphere of controlled humidity and temperature.

It is not easy to determine the maximum or true inherent moisture of a coal because it is first necessary to obtain equilibrium at 100 per cent. humidity, under which conditions free or surface

APPENDIX A-2

Stansfield, E., Lang, W.A., Sutherland, J.W., Gilbert, K.C. and Zeavin, S., 1927: Specific gravity of coal; Scientific and Industrial Research Council of Alberta, Report No. 22, p. 21 - 23.

Stansfield E., Lang, W.A., Gilbart, K.C. and Reuben, S., 1922: Scientific and Industrial Research Council of Alberta, Rept. No. 22.

minations were also made on the same coals, after these had been exposed to a current of air at 105°C for six hours: but these results have been omitted from the table. The oxidisability of a coal, as measured by this test, increases with oxidation in hot air. In the same way a weathered coal gives a higher value than a fresh coal from the same mine. It will thus be seen that as a coal matures from lignitic to anthracitic character its oxidisability decreases, but if coal of any character becomes weathered its oxidisability increases, and its apparent maturity decreases.

SPECIFIC GRAVITY OF COAL.

Determinations have been made of the specific gravity of a number of coal samples. The samples were separated by hand into portions of differing cleanliness, where this was possible, and the specific gravity and analysis of each portion determined. In some cases samples of bone coal were also tested in order to get a wide range of ash content.

Two specific gravities are reported, "apparent" and "real". A lump of coal normally contains many microscopic cells filled with air or gas. The apparent specific gravity is the specific gravity of the lump as it occurs. The real specific gravity is that of the coal substance. The apparent specific gravity is the value to be employed for calculating the weight of a cubic foot of coal as mined and for similar practical applications, but as the real specific gravity can be determined with the greater accuracy, both values are given. The relation between the two values is an indication of the porosity of the coal, the greater the difference between the two values the greater the porosity.

The mineral impurities in a coal are denser than the coal substance, so that, with a few exceptions noted below, the density of any coal increases with the ash. In the table of values reported a number of minor discrepancies will be noticed where a slight increase in ash is accompanied by a decrease in specific gravity. This may be due to a variation either in the coal or in the mineral impurity. It has been noted that with certain coals there is a minimum specific gravity with approximately 3 or 4 per cent. of ash. From this point the density increases with either an increase or a decrease of the ash. It is probable that these extremely low ash samples of coal are largely vitrain and contain little or no fusian or animal charcoal.

The specific gravity changes not only with the ash content of the sample but also with its moisture content. When a lump of high moisture coal dries out the lump shrinks and checks, but it also becomes more porous, so that the apparent specific gravity decreases. No data has yet been collected to correlate the apparent specific gravity of a sample with its moisture content. On the other hand, as the moisture which escapes has a specific gravity of unity and the dry coal substance has a specific gravity of about 1.3 the more the sample dries out the higher its real specific gravity becomes. It has not yet been possible to determine the change of real specific gravity over a wide range of moisture content, but within

narrow limits it can be assumed that a decrease of 1% in the moisture content will increase the real specific gravity 0.004 with samples of 1.3 specific gravity, and 0.006 with samples of 1.4 specific gravity.

The results reported in Table III show the moisture and ash content of each portion tested, as well as the determined specific gravities. Slight adjustments have been made in the reported real specific gravities to adjust these values to the same moisture content as for the reported apparent specific gravities. It is hoped eventually to prepare curves showing the relations between the moisture and ash and the specific gravities of different samples of a series of typical coals of the province, but too few determinations have so far been made.

A number of determinations were made of samples taken in 1927, but as the technique of the determination was subsequently improved, the only values reported in the table are those of samples taken early in 1928.

TABLE III.—SPECIFIC GRAVITIES OF COAL AND BONE COAL.

Sample No. Mine and Area	Moisture %	Ash %	Specific Gravity	
			Apparent	Real
(a) Bituminous Coals.				
14-28	1.2	4.6	1.289	1.319
Mountain Park	1.1	4.9	1.279	1.325
Mountain Park Area	0.6	6.4	1.289	1.342
13-28	0.9	7.4	1.329	1.360
Blue Diamond	1.0	7.7	1.326	1.351
Brule Area	0.8	11.2	1.385	1.415
17-28	1.1	3.0	1.306	1.333
Dennison	1.2	10.9	1.378	1.397
Crowsnest Area	0.8	29.6	1.583	1.625
305-28	5.8	1.9	1.328	1.371
Christine	5.2	2.8	1.344	1.386
Crowsnest Area	6.6	5.9	1.365	1.401
(b) Sub-bituminous Coals.				
304-28	7.2	5.1	1.335	1.387
Saunders Ridge	7.3	6.9	1.363	1.389
Coalspur Area	6.9	9.2	1.393	1.424
313-28	9.1	3.3	1.334	1.357
Alexo Mine	7.1	5.0	1.317	1.350
Saunders Area	7.4	12.1	1.385	1.424
314-28	5.5	4.1	.....	1.326
Du Rocher	6.0	5.0	1.312	1.343
Pekisko Area	6.3	11.5	1.409	1.439
18-28 & 316-28	4.3	7.5	1.319	1.333
Rhodes Mine	4.1	9.3	1.332	1.358
Pincher Area	4.2	13.9	1.359	1.389
	4.7	17.2	1.384	1.414
	5.1	21.0	1.424	1.453
312-28	5.8	7.2	1.351	1.384
Beazer	5.6	8.1	1.357	1.395
Magrath Area	5.2	11.4	1.381	1.422
301-28	10.3	5.1	1.321	1.355
Lethbridge	9.2	5.8	1.324	1.338
Lethbridge Area	10.5	10.6	1.366	1.381
21-28	10.2	6.0	1.329	1.346
Galt	11.9	10.9	1.378	1.400
Lethbridge Area	12.5	11.6	1.360	1.380
	10.0	12.8	1.388	1.406

(c) Domestic Coals.

Sample No. Mine and Area	Moisture %	Ash %	Specific Gravity	
			Apparent	Real
308-28	15.0	6.2	1.338	1.366
Bridge End	14.7	7.0	1.354	1.378
Taber Area	14.2	7.4	1.356	1.383
309-28	24.8	3.6	1.309	1.327
Anon	20.3	5.9	1.331	1.358
Taber Area	19.6	8.3	1.345	1.394
311-28	14.1	3.8	1.325	1.348
Aborn	12.7	7.0	1.342	1.364
Milk River Area	12.2	16.1	1.430	1.461
310-28	20.9	4.1	1.312	1.324
Hughson	19.1	7.4	1.347	1.381
Milk River Area	17.8	10.6	1.393	1.411
307-28	17.6	3.8	1.322	1.361
Pembina	18.3	5.2	1.340	1.370
Pembina Area	17.7	7.1	1.351	1.392
324-28	24.9	4.3	1.311	1.325
Cardiff	27.4	4.8	1.298	1.317
Edmonton Area	25.2	5.0	1.315	1.328
	21.1	15.0	1.385	1.397
319-28	24.2	3.9	1.286	1.331
Black Diamond	22.6	8.0	1.337	1.360
Edmonton Area	21.5	8.8	1.332	1.362
318-28	26.4	3.1	1.281	1.320
Dobell	25.2	3.8	1.274	1.325
Tofield Area	24.8	7.4	1.318	1.343
317-28	24.1	4.4	1.300	1.332
Stoney Creek	23.8	5.2	1.316	1.343
Camrose Area	.....	.....	.....	.....
320-28	27.0	7.2	1.332	1.349
O.K.	24.1	12.6	1.360	1.378
Castor Area	25.5	16.3	1.402	1.415
306-28	25.0	4.8	1.305	1.332
New Walker	26.3	5.3	1.309	1.335
Sheerness Area	25.4	9.9	1.339	1.362
323-28	18.8	4.3	1.329	1.369
Carbondale	18.0	7.8	1.336	1.396
Ardley Area	17.2	9.0	1.352	.....
	19.6	8.8	.....	1.403
322-28	19.9	3.4	1.328	1.354
Big Valley	21.9	5.6	1.331	1.355
Big Valley Area	.....	.....	.....	.....
321-28	14.1	7.4	1.348	1.380
Carbon Black	15.7	7.8	1.351	1.375
Carbon Area	14.4	8.0	1.352	1.376
302-28	19.5	2.3	1.320	1.340
Elgin	19.6	3.8	1.314	1.336
Drumheller Area	19.4	4.0	1.315	1.336
19-28	17.4	3.5	1.308	1.331
Hy Grade	17.0	3.7	1.309	1.333
Drumheller Area	16.4	15.4	1.398	1.417
	16.0	22.7	1.454	1.472
303-28	18.9	3.2	1.319	1.342
Midland	18.3	7.0	1.333	1.353
Drumheller	18.3	7.6	1.335	1.354
16-28	12.2	5.3	1.336	1.363
Popovich and Vanbesien	12.5	5.7	1.342	1.368
Champion Area	12.8	6.0	1.347	1.368
315-28	13.4	6.9	1.356	1.376
Ellis	.....	.....	.....	.....
Champion Area	.....	.....	.....	.....